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THESIS

DYNAMIC ANALYSIS OF THE LOW POWER
ATMOSPHERIC COMPENSATION
EXPERIMENT (LACE) SPACECRAFT

by

Wesley F. Walters

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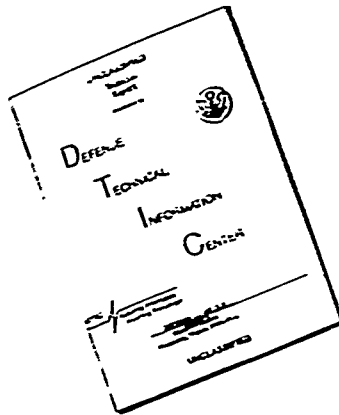
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COMPENSATION EXPERIMENT (LACE) SPACECRAFT

by

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Major, United States Army
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ABSTRACT

The Low Power Atmospheric Compensation Experiment (LACE) spacecraft was launched for NRL in February 1990. The LACE flight dynamics experiment will provide on-orbit systems identification of the LACE spacecraft. The experiment is designed to measure modal frequencies, damping ratios, and oscillation amplitudes of the LACE spacecraft. The purpose of this study is to develop a finite element model of the LACE spacecraft and conduct a dynamics analysis to determine natural frequencies and mode shapes. Four configurations of the spacecraft are analyzed. This data will be compared with actual orbital data and will provide an opportunity for improvements in the accuracy of computer simulations of flexible structures and multi-body dynamics. Thermoelastic effects due to differential heating are addressed to check the magnitude of deformations that may cause a problem for stability or on-orbit identification. The final phase of this study is to conduct a parametric analysis of the spacecraft boom to investigate the presence of chaotic vibration for combinations of excitation amplitude and frequency.



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I. INTRODUCTION

A. PURPOSE

This study is concerned with the modeling and analysis of the Low Power Atmospheric Compensation Experiment (LACE) spacecraft. One of the missions of the LACE spacecraft is to conduct and obtain flight data for on-orbit system identification. The flight dynamics experiment is designed to measure modal frequencies, damping ratios, oscillation amplitude of the LACE spacecraft and vibration intensity generated by boom deployments and retractions. This experiment will provide an opportunity for improvements in the accuracy of computer simulations of large flexible space structures and multi-body dynamics.

It will also provide a mechanism for evaluating influence of magnetic torques, gravity gradient torques and atmospheric drag on the LACE-type structures.

The purpose of this study is to develop a finite element model of the LACE spacecraft using the finite element program Graphical Interactive Element Total System (GIFTS). Dynamic analysis is performed on the model to determine the natural frequencies and mode shapes. Thermoelastic effects due to differential heating are addressed to check if the magnitude of deformations could cause a problem for stability or system

identification. Finally, a parametric analysis is conducted on a model of the spacecraft boom to investigate the possibility of chaotic vibrations that may be induced during the mission.

B. OVERVIEW/BACKGROUND

1. Spacecraft Description

NRL-developed LACE was successfully launched on February 14, 1990, from Cape Canaveral on a DELTA II launch vehicle. The spacecraft incorporates three deployable/retractable booms of maximum length 150 feet. The 2,800 lb. LACE spacecraft is stabilized by a 150 ft. zenith directed gravity gradient boom mounted on top of the spacecraft, a momentum wheel with axis along the pitch axis and a magnetic damper at the tip of the gravity gradient boom. The retroreflector boom is mounted forward and deployed along the velocity vector, while the balance boom is mounted and pointed aft. Figure 1 shows the basic configuration of the spacecraft.

2. Experimental Hardware

The flight dynamics experiment hardware consists of three germanium corner cubes mounted on the lead boom, on the bottom of the bus and on the aft balance boom to serve as targets for the 10.6 micron Firepond laser radar at MIT Lincoln Laboratory, Lexington, Massachusetts. The Firepond laser has a 4 millisecond square wave pulse at a frequency of 62.5 Hz and pulse energy of 3.2 joules. The Firepond laser radar will illuminate the cubes to measure the relative motion

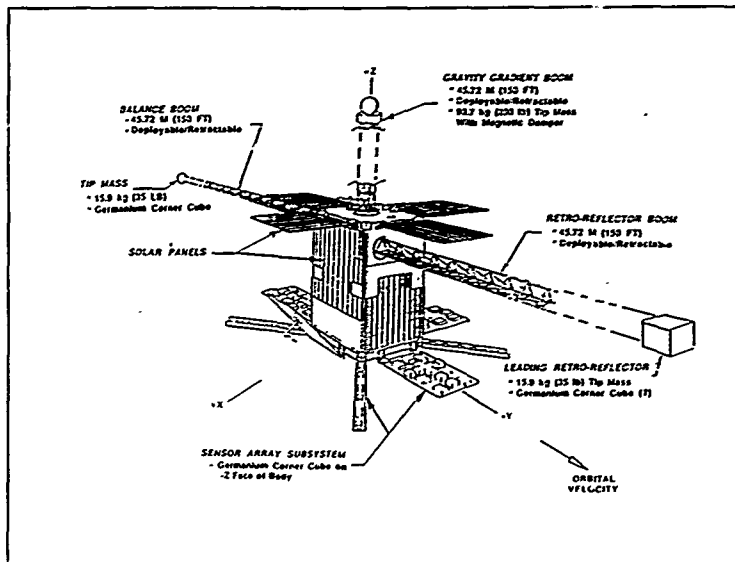


Figure 1. LACE Spacecraft Configuration

of the boom with respect to the main body. Reflections from the corner cubes will give differential Doppler information on the magnitude of the displacement rates due to boom flexure. [Ref. 1]

The Ultra-Violet Plume Instrument (UVPI) will be used to measure the absolute bus rotation rate. It has the capability of resolving angular velocities of 5×10^{-5} radian/sec. [Ref. 2]

Figure 2 depicts the LACE flight dynamics experiment.

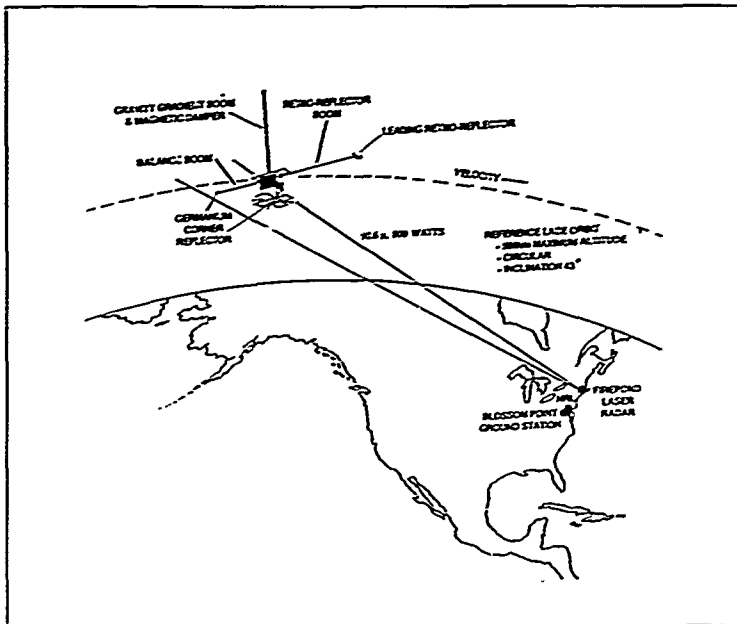


Figure 2. LACE Flight Dynamics Experiment

3. Acquisition Sequence

The recommended acquisition sequence for the LACE spacecraft calls for four different boom deployments. Initially, the gravity gradient will be extended to 75 feet. After the spacecraft has stabilized, the boom will be deployed to 150 feet and the momentum wheel will be spun up. Then the leading (retroreflector) and tracking (balance) booms will be extended to 119.5 feet. The final configuration will have the retroreflector boom and gravity gradient boom extended to 150 feet and the trailing balance boom extended to 75 feet.

4. Orbital Parameters

Table I lists the orbital parameters for LACE.

Table I. LACE ORBITAL PARAMETERS

Altitude	541 km
Period	95.47 min
Inclination	43.087 degrees
Eccentricity	.00108
Semi-major Axis	6919.351 km

C. MOTIVATION

During the past five years, system identification of flexible space structures has emerged as an important problem. Many proposed space missions will involve large space structures that are very flexible, contain thousands of structural elements and have special mission requirements, such as pointing accuracies. Some of these structures include space defense platforms, solar power stations and manned laboratories, such as the space station. These structures may require some type of active control to carry out ongoing maneuvers, suppress and control vibration and achieve accurate and reliable pointing. An obstacle to meeting some of these objectives can be attributed to the inability to analytically model the structural dynamics of these highly flexible structures with a high degree of confidence or precision. Typically, such information is also required in the design of vibration suppression and control systems.

The inability to model dynamics of large flexible structures is caused by four factors:

1. Because of launch costs, large space structures are constructed out of very light composites and cannot support their weight in gravity. This prevents ground-based testing.
2. New composite materials will result in modeling uncertainty of the material properties.
3. Complications arise from the combination of very high flexibility and large thermal gradients.
4. On-orbit structure will be exposed to harsh space environments which include particle radiation, solar effects, gravitational anomalies, extreme temperatures and near vacuum. The structure may undergo physical parameter changes. [Ref. 3]

General purpose structural modeling and multi-body dynamics computer programs such as GIFTS and TREESTOPS, respectively, can be used to define and investigate complex space structures. However, there is no assurance that optimum structural models can be generated with these programs. It is envisioned that the on-orbit data received from LACE can be used to improve these computer models.

D. THESIS OUTLINE

This study contains eight chapters. The second chapter provides a discussion of the theoretical basis adopted by GIFTS to develop a finite element model and provide dynamic analysis. Chapter III describes the development of the simple beam model and complex finite element model of the LACE spacecraft. Chapter IV provides the natural frequencies and

mode shapes of the spacecraft. In Chapter V a thermoelastic analysis is conducted on the LACE spacecraft boom to determine the effects of differential heating. Chapter VI discusses multi-body dynamics and describes a multi-body program called TREETOPS. Chapter VII gives a description and a method to identify chaotic vibrations. A parametric analysis of the LACE spacecraft boom modeled as a single degree of freedom system is provided to determine if chaotic vibrations may be induced. The model uses experimental data for stiffness, mass and damping and examines the behavior for possible chaos in the system. Chapter VIII contains conclusions and scope for future research.

II. THEORETICAL FORMULATION

2. FINITE ELEMENT METHOD

The finite element method is a numerical procedure to compute the response of complex structures. The basic unit of this analysis, the discrete finite element, is a geometrically simplified representation of a small part of the physical structure. The finite element method views the complete complex structure as an assembly of a finite number of these finite discrete elements (beams, rods, plates, etc.), each of whose properties and deformation responses are simple, as compared to the complete structure. The division of the discrete elements is natural, in general, and follows the way the actual structure is built (truss members, frames, etc.). The elements interconnect at nodes where the elements meet and move in unison only after compatibility requirements are met. This assures that adjacent elements will not overlap or separate.

Each node has six degrees of freedom with three deflections and three rotations. Based on how the elements are connected at the rods, the computed properties of the individual elements are determined and assembled to obtain the equivalent, but more complex properties of the entire assembled model. The structural model created can then be used

to predict the behavior of the real structure. In this study, the structural model will be used to determine the structure's natural frequencies and mode shapes. The finite element types used to model the LACE spacecraft include rod, beam and plate/shell elements. These elements will be discussed further in accordance with the theory adopted used by GIFTS.

1. Rod Elements

Rod elements are pin-jointed truss members that are capable of carrying axial forces only. Figure 3 shows a typical rod element.

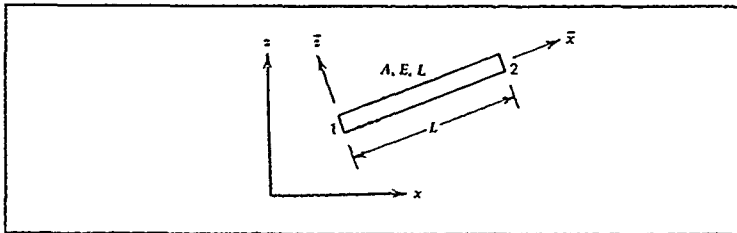


Figure 3. Rod Elements

The element is located in the $(x-y-z)$ coordinate system, which is also known as the reference or global coordinate system. Coordinates along the element are the local or element coordinate system $(\bar{x}-\bar{y}-\bar{z})$.

The following derivations can be found in more detail in Allen and Haisler [Ref. 4: section 7.2]. The element stiffness matrix, derived from the principle of virtual work, in local coordinate system, is defined by the equation

$$[\bar{K}] = \frac{AE}{L} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \quad (1)$$

The matrix $[\bar{K}]$ represents the truss element stiffness matrix in the local coordinate system.

Figure 4 shows the rod element oriented at a positive angle θ relative to the global axis.

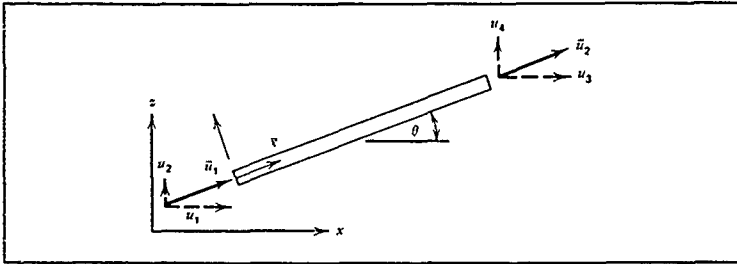


Figure 4. Rod Element at θ

Element and global displacements at nodes 1 and 2 are related by

$$\begin{Bmatrix} \bar{u}_1 \\ \bar{u}_2 \end{Bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 & 0 \\ 0 & 0 & \cos\theta & \sin\theta \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{Bmatrix} \quad (2)$$

or

$$\{\bar{u}\} = [T] \{u\} \quad (3)$$

where

$$[T] = \begin{bmatrix} \cos\theta & \sin\theta & 0 & 0 \\ 0 & 0 & \cos\theta & \sin\theta \end{bmatrix} \quad (4)$$

Using the strain energy equation and the matrix product transpose rule, the following relations are derived:

$$\begin{aligned} u &= \frac{1}{2} \{\bar{u}\} [\bar{K}] \{\bar{u}\} \\ &= \frac{1}{2} \{u\} [K] \{u\} \end{aligned} \quad (5)$$

where

$$[K] = [T]^T [\bar{K}] [T] \quad (6)$$

Therefore, using equations (1) and (6), $[K]$ is transformed to the global coordinate system to obtain

$$K = \frac{AE}{L} \begin{bmatrix} c^2 & cs & -c^2 & -cs \\ cs & s^2 & -cs & -s^2 \\ -c^2 & -cs & c^2 & cs \\ -cs & -s^2 & cs & s^2 \end{bmatrix} \quad (7)$$

where $c = \cos \theta$ and $s = \sin \theta$.

2. Beam Elements

Beam elements are characterized as members that are capable of resisting bending. The beam element will carry axial forces, shear forces and bending moments. Figure 5 depicts a typical planar beam finite element.

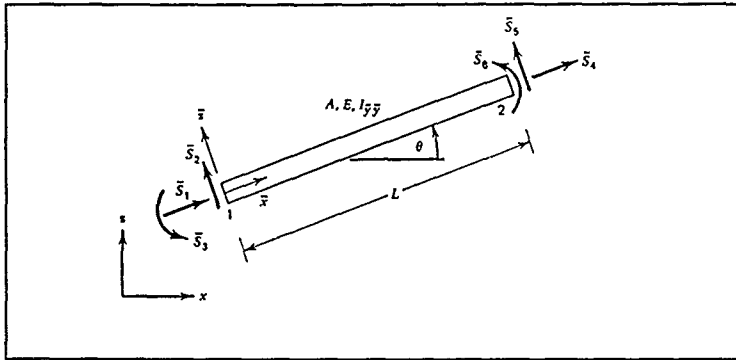


Figure 5. Beam Element

The following can be found in more detail in Allen and Haisler [Ref. 4: section 7.3.]

The stiffness matrix is defined by the equation

$$[\bar{K}] = \begin{bmatrix} \frac{EA}{L} & 0 & 0 & -\frac{EA}{L} & 0 & 0 \\ 0 & \frac{12EI}{L^3} & \frac{6EI}{L^2} & 0 & -\frac{12EI}{L^3} & \frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{4EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{2EI}{L} \\ -\frac{EA}{L} & 0 & 0 & \frac{EA}{L} & 0 & 0 \\ 0 & -\frac{12EI}{L^3} & -\frac{6EI}{L^2} & 0 & \frac{12EI}{L^3} & -\frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{2EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{4EI}{L} \end{bmatrix} \quad (8)$$

where $I = I_{yy}$.

In order to assemble the stiffness matrices, they must be transformed to global coordinates. The local-global transformation, as before, is given by

$$[T] = \begin{bmatrix} c & s & 0 & 0 & 0 & 0 \\ -s & c & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & c & s & 0 \\ 0 & 0 & 0 & -s & c & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (9)$$

where $c = \cos \theta$ and $s = \sin \theta$.

The remainder of the finite element formulation is similar to the previous section on rod elements. The stiffness matrix in global coordinates is constructed using equations (6), (8) and (9).

3. Plate Bending Theory

A flat plate, like a beam, supports transverse loads and offers resistance to bending. Figure 6 shows stresses that act on a homogeneous linearly elastic plate.

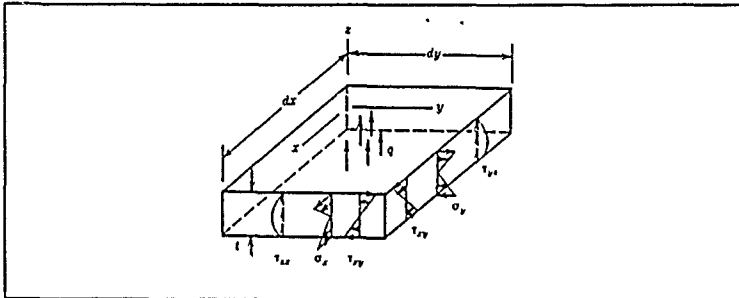


Figure 6. Plate Stresses

The normal stresses σ_x and σ_y vary linearly with z and contribute to bending moments M_x and M_y .

The normal stress σ_z is negligible when compared with σ_x , σ_y and τ_{xy} . The transverse shear stresses τ_{yz} and τ_{zx} vary quadratically with z . Plate bending in this analysis refers to external loads perpendicular to the xy plane and applied moments. [Ref. 5]

The stresses shown in Figure 6 result in the following equations [Ref. 5] for bending moments M and transverse shears Q .

$$M_x = \int_{-t/2}^{t/2} \sigma_x z dz \quad M_y = \int_{-t/2}^{t/2} \sigma_y z dz \quad M_{xy} = \int_{-t/2}^{t/2} \tau_{xy} z dz \quad (10a)$$

$$Q_x = \int_{-t/2}^{t/2} \tau_{zx} dz \quad Q_y = \int_{-t/2}^{t/2} \tau_{yz} dz \quad (10b)$$

Stresses σ_x and σ_y are greatest at the surface $z = \pm t/2$, while τ_{xy} is maximum at the midsurface. Transverse shear stresses τ_{yz} , τ_{zx} are small compared to σ_x , σ_y and τ_{xy} , and are not considered in the classical Kirchhoff plate theory.

In what follows, Kirchhoff's plate theory [Ref. 5] is briefly reviewed, which forms the basis for the GIFTS formulation.

As transverse loads are applied to the plate, the points on the midsurface move only in the z direction. Under loads, normals to the midsurface are assumed to remain normal before and after deformation. Figure 7 shows a differential element of a thin plate before and after loading. As shown, the line OP is perpendicular to the midsurface before and after loading.

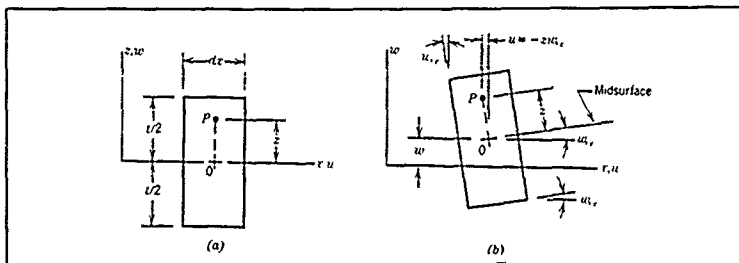


Figure 7. Differential Element of a Thin Plate a) Before Loading b) After Loading

From Figure 7, with $\frac{\partial w}{\partial x}$ and $\frac{\partial w}{\partial y}$ being assumed as small angles, the following relations apply:

$$\begin{aligned}
 u &= -z \frac{\partial w}{\partial x} & \text{hence} & & e_x &= \frac{\partial u}{\partial x} = -z \frac{\partial^2 w}{\partial x^2} \\
 v &= -z \frac{\partial w}{\partial y} & & & e_y &= \frac{\partial v}{\partial y} = -z \frac{\partial^2 w}{\partial y^2} \\
 \gamma_{xy} &= \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = -2z \frac{\partial^2 w}{\partial x \partial y}
 \end{aligned} \tag{11}$$

These are the strain displacement relations in accordance with classical Kirchhoff's plate theory applied to a thin plate.

By using stress-strain relations, the moment-curvature relations may be derived. Neglecting thermal expansion and assuming isotropic material, stress-strain relations are given by:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \frac{E}{(1-\nu^2)} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} \quad (12)$$

By substituting equation (11) into equation (12) and substituting the result into equation (10a), the following is obtained:

$$\{M\} = -[D_k] \{\kappa\} \quad (13)$$

where the moments and curvatures are

$$\{M\} = [M_x, M_y, M_{xy}]^T ; \quad \{\kappa\} = \left[\frac{\partial^2 w}{\partial x^2}, \frac{\partial^2 w}{\partial y^2}, 2 \frac{\partial^2 w}{\partial x \partial y} \right] \quad (14)$$

and

$$[D_k] = D \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{(1-\nu)}{2} \end{bmatrix} \quad (15)$$

where $D = \frac{Et^3}{12(1-\nu^2)}$. D is called the flexural rigidity of the plate and is analogous to bending stiffness EI of a beam.

The next step is to formulate the element stiffness matrix using the virtual work equation:

$$\delta w_{int} = \int_v \frac{1}{2} \{\delta \epsilon\}^T [E] \{\delta \epsilon\} dv \quad (16)$$

where

$$\{e\}^T = \left[-z \frac{\partial^2 w}{\partial x^2} - z \frac{\partial^2 w}{\partial y^2} - 2z \frac{\partial^2 w}{\partial x \partial y} \right]$$

and where $[E]$ is given by equation (12). δw_{int} and δe are the internal virtual work and virtual strains respectively.

For plates, using the strain-displacement relations,

$$\delta w_{int} = \int_A \frac{1}{2} \{ \kappa \}^T [D] \{ \kappa \} dA, \text{ where } \{ \kappa \}^T = \left[\frac{\partial^2 w}{\partial x^2} \frac{\partial^2 w}{\partial y^2} \frac{\partial^2 w}{\partial x \partial y} \right] \quad (17)$$

For an element having N nodes, displacements w is interpolated as

$$w = \frac{1}{3 \times 3N} \{N\} \{d\} \quad (18)$$

where the nodal degrees of freedom are given by

$$\{d\} = \left[w_1 \frac{\partial w}{\partial x_1} \frac{\partial w}{\partial y_1} \dots w_N \frac{\partial w}{\partial x_N} \frac{\partial w}{\partial y_N} \right]^T$$

Equation (18) is differentiated to yield curvatures

$$\{ \kappa \} = \frac{[B]}{3 \times 3N} \{d\} \quad (19)$$

On substituting equation (19) into equation (17) yields

$$\delta w_{int} = \{ \delta d \}^T [K] \{d\} \quad (20)$$

where the element stiffness matrix $[K]$ is identified as

$$[K]_{3N \times 3N} = \int_A [B]^T [D] [B] dA \quad (21)$$

B. FREE VIBRATION OF MULTI-DEGREE-OF-FREEDOM SYSTEMS

Craig [Ref. 6] provides a good overview of multi-degree-of-freedom (MDOF) systems.

The equation of motion for a free undamped MDOF system can be written as

$$[m] \{\ddot{u}\} + [K] \{u\} = \{0\} \quad (22)$$

where $[m]$ and $[K]$ are $(N \times N)$ matrices and $\{u(t)\}$ is a $N \times 1$ vector of generalized displacement coordinates. The solution of the differential equation gives harmonic motion given by

$$u = u_0 \cos(\omega t - \alpha) \quad (23)$$

Substituting equation (23) into (22) yields the eigenvalue problem

$$([K] - \omega^2 [m]) \{u\} = 0 \quad (24)$$

For non-trivial solution,

$$|K - \omega^2 m| = 0 \quad (25)$$

Equation 25 is recognized as the characteristic equation for the free vibration response. The resulting polynomial in ω^2 yields the roots or the eigenvalues which correspond to the natural frequencies of the system.

Corresponding to each eigenvalue, w_r^2 , there will be an eigenvector or natural mode u_r , where

$$u_r = \begin{Bmatrix} u_1 \\ u_2 \\ \vdots \\ u_n \end{Bmatrix} \quad r = 1, 2, \dots, N \quad (26)$$

Typically, these modes may be scaled by a process called normalization and results in modal vectors called normal modes. A mode that has been scaled to have a unique amplitude will be designated as ϕ_r and will be dimensionless. The modal vector corresponding to w_r can be written

$$\mu_r = c_r \phi_r \quad (27)$$

where c_r is a scaling constant whose units are such that $\phi_r^T m \phi_r$ has the dimension of mass.

There are three procedures for normalizing modes for MDOF systems. [Ref. 6]

1. Scale the r^{th} mode so that $(\phi_i)_r = 1$ at a specified coordinate i .
2. Scale the r^{th} mode so that $(\phi_i)_r = 1$, where $|(\phi_i)_r| = \max_j |(\phi_j)_r|$.
3. Scale the r^{th} mode so that the generalized mass is defined by

$$m_r = \phi_r^T m \phi_r \quad (28)$$

The generalized stiffness for the r^{th} mode is

$$K_r = \phi_r^T k \phi_r \quad (29)$$

By expressing equation (24) for the r^{th} mode and premultiplying by ϕ_r^T , the generalized stiffness-mass relations are obtained as

$$K_r = \omega_r^2 m_r \quad (30)$$

C. NUMERICAL EVALUATION OF MODES AND FREQUENCIES OF MDOF SYSTEMS

This section discusses the procedure used by GIFTS to obtain numerical solution to large eigenproblems. The LACE spacecraft in its fully deployed state was modeled by over 16,000 degrees of freedom. The dynamic analysis of this structure involves determining the natural frequencies and the corresponding natural modes by solving the equation

$$(K - \omega_i^2) \phi_i = 0 \quad (31)$$

Vector iteration methods are simple and elegant for obtaining eigenpairs. The specific method used by GIFTS is the subspace iteration method. The subspace iteration solution is very effective in the calculation of the lowest eigenvalue and corresponding eigenvectors of systems with large bandwidth and which are too large for the high-speed storage of the computer. [Ref. 7]

Bathe [Ref. 8] establishes three steps for the subspace iteration method.

1. Establish q starting iteration vectors, $q > p$, where p is the number of eigenvalues and vectors to be calculated.
2. Use simultaneous inverse iteration on the q vectors and Ritz analysis to extract the best eigenvalue and eigenvector approximations from the q iteration vectors.
3. After convergence, the Sturm sequence check is used to verify that the required eigenvalues and corresponding eigenvectors have been calculated.

The objective of the subspace iteration method is to solve for the lowest p eigenvalues and eigenvectors satisfying

$$K\phi = M\phi\Lambda \quad (32)$$

where Λ = diagonal (λ_i) and $\phi = [\phi_1, \dots, \phi_p]$. The eigenvectors must also satisfy the orthogonality conditions

$$\phi^T K \phi = \Lambda; \quad \phi^T M \phi = I \quad (33)$$

Detailed derivations of the subspace iteration method are shown in Bathe [Ref. 8]. The subspace iteration algorithm shown below finds an orthogonal basis of vectors in E_{L+1} subspace.

$$K\bar{X}_{L+1} = M X_L \quad (34)$$

for $L=1, 2, \dots$, and with iterations from E_L to E_{L+1} . Next, projections of the operators K and M onto K_{L+1} are computed:

$$K_{L+1} = \bar{X}_{L+1}^T K \bar{X}_{L+1} \quad (35)$$

$$M_{L+1} = \bar{X}_{L+1}^T M \bar{X}_{L+1} \quad (36)$$

By solving for the eigensystem of projected operators

$$K_{L+1} Q_{L+1} \approx M_{L+1} Q_{L+1} \Lambda_{L+1} \quad (37)$$

where Q is an orthogonal matrix, improved approximation for the eigenvectors is found by

$$\bar{X}_{L+1} = \bar{X}_{L+1} Q_{L+1} \quad (38)$$

It may be noted that $\Lambda_{L+1} \rightarrow \Lambda$ and $\bar{X}_{L+1} \rightarrow \Phi$ as $L \rightarrow \infty$.

The first step of the subspace iteration is to generate the starting iteration vectors in \bar{X}_1 . The following algorithm is used to select the starting iteration vector. The first column in $M\bar{X}_1$ is the diagonal of M . The other columns are unit vectors with entries +1 at coordinates with the smallest k_{ii}/m_{ii} ratio.

The subspace iteration method requires a measure to compute convergence. Assuming that in $(L-1)$ and L iterations, eigenvalue approximations $\lambda_i^{(L)}$ and $\lambda_i^{(L+1)}$, $i=1, \dots, p$, have been calculated. The measure for convergence, then, is

$$\frac{|\lambda_i^{(L+1)} - \lambda_i^{(L)}|}{\lambda_i^{(L+1)}} \leq \text{tol} ; i = 1, \dots, p. \quad (39)$$

where tol may be 10^{-25} , when eigenvalues shall be accurate to 25 digits.

Since equations (32) and (33) can be satisfied by any eigenpairs, there must be a way to verify the calculations. Once the convergence is satisfied in equation (39), with s being at least equal to 3, a check may be performed to make sure that the smallest eigenvalues and corresponding eigenvectors have been calculated. The Sturm sequence property is used to provide this check. This property is derived from the following analysis. [Ref. 8] By using the Gauss elimination solution, the stiffness matrix can be factorized as

$$K = LDL^T \quad (40)$$

where L is a lower unit triangular matrix and D is the diagonal matrix.

Let $K - \mu M$ be factorized into LDL^T . In the decomposition of $K - \mu M$, the number of negative elements in D is equal to the number of eigenvalues smaller than μ . Because of this property, by assuming a shift μ and checking whether μ is smaller or larger than the required eigenvalue, successive iterations can reduce the interval in which the eigenvalue must be. A summary of subspace iteration solution is shown in Table II.

Table II. SUMMARY OF SUBSPACE ITERATION

Operation	Calculation	NUMBER OF OPERATIONS			Required Storage
		$m = m_k, m_k = 0$	$m = m_k, m_k = 1$	$m = m_k, m_k = 2$	
Factorization of K	$K = LDL^T$	$\frac{1}{2}nm^2 + \frac{1}{2}nm$	$\frac{1}{2}nm^2 + \frac{1}{2}nm$	$\frac{1}{2}nm^2 + \frac{1}{2}nm$	Algorithm is effectively implemented as out-of-core solver
Subspace Iteration	$K\tilde{X}_{k+1} = Y_k$	$nq(2m+1)$	$nq(2m+1)$	$nq(2m+1)$	
	$K\tilde{X}_{k+1} = \tilde{X}_{k+1}^T Y_k$	$\frac{1}{2}nq(q+1)$	$\frac{1}{2}nq(q+1)$	$\frac{1}{2}nq(q+1)$	
	$\tilde{Y}_{k+1} = M\tilde{X}_{k+1}$	$nq(2m+1)$	$nq(2m+1)$	nq	
	$M_{k+1} = \tilde{X}_{k+1}^T \tilde{Y}_{k+1}$	$\frac{1}{2}nq(q+1)$	$\frac{1}{2}nq(q+1)$	$\frac{1}{2}nq(q+1)$	
Sturm sequence check	$K_{k+1}Q_{k+1} = M_{k+1}Q_{k+1}A_{k+1}$	nq^2	nq^2	$O(q^3)$ neglected	
	$\tilde{Y}_{k+1} = \tilde{Y}_{k+1}Q_{k+1}$	$n(m+1)$	$n(m+1)$	n	
	$\tilde{K} = K - \mu N$	$\frac{1}{2}nm^2 + \frac{1}{2}nm$	$\frac{1}{2}nm^2 + \frac{1}{2}nm$	$\frac{1}{2}nm^2 + \frac{1}{2}nm$	
	$\tilde{K} = LDL^T$	$4nm + 5n$	$4nm + 5n$	$2nm + 5n$	
Error estimates	$\frac{\ K\tilde{G}_k^{(p+1)} - \tilde{X}_k^{(p+1)}M\tilde{G}_k^{(p+1)}\ _2}{\ K\tilde{G}_k^{(p+1)}\ _2}$	$nm^2 + nm(4+p) + 5np$	$nm^2 + nm(4+p) + 5np$	$nm^2 + nm(3+2p) + 5np$	
	Total for solution of p lowest eigenvalues and associated eigenvectors, assuming that ten iterations are required and $q = \min\{2p, p+8\}$	$nm^2 + 20nq(2m+q+\frac{1}{2})$	$nm^2 + 20nq(2m+q+\frac{1}{2})$	$nm^2 + 20nq(m+q+\frac{1}{2})$	

III. LACE FINITE ELEMENT MODEL

A. GIFTS CAPABILITIES

GIFTS has several capabilities which facilitate the modeling of large complex structures. Some of these capabilities include:

1. automatic model generation
2. model editing, display and information
3. automatic load and boundary conditions
4. vibrational mode extraction
5. substructuring
6. thermal stress analysis

Element types that can be used include:

1. rods and beams
2. plates/shells
3. solid elements and axisymmetric elements [Ref. 9]

The elements can be selected from a library of options. The materials can be created by the user or from a library of defined materials. GIFTS also allows users to define anisotropic materials.

Static and dynamic analysis can be performed on the model. The dynamic analysis provides free vibrations and mode shapes. These vibrational mode shapes can be displayed on the screen. For structures that undergo thermal loading, deflections and

stresses can be calculated by computing thermal (pseudo-forces) forces to simulate the thermal effects.

GIFTS also has the capability for substructuring and multi-level substructuring. Large models may be divided into substructures. Certain areas of a substructure may be modeled as a second level substructure to allow economic modeling and reduce computational costs.

B. SIMPLE FINITE ELEMENT MODEL OF LACE

Initially, the LACE spacecraft is modeled as a point mass with three attached beam members. The three dimensional triangular trusses are modeled as solid circular beams. To ensure that this beam had the same bending characteristics, the following bending stiffness relations was used from AEC-Able Engineering [Ref. 10].

$$\text{flexural rigidity } (EI) = 1.5 \pi ER^4 e^2 \quad (41)$$

where

e = maximum bending strain of longerons when completely coiled ($e = d/2R = F/E$)
 F = coiling stress of longerons
 d = longeron diameter
 E = Young's modulus of longeron material
 R = boom radius

with

$e = .015$
 $R = 5.0 \text{ inches}$
 $E = 8.0 \times 10^6 \text{ psi}$

This results in $EI = 5.3 \times 10^6 \text{ lbs-in}^2$.

From this relation, I is seen to be .663 which results in a solid circular beam with a radius of .9583 inches. The beam is with 10 elements for a 150 foot truss and 5 elements for a 75 ft. truss. This model is used in GIFTS with the appropriate tip masses to determine the natural frequencies and mode shapes. The results will be shown and discussed in the next chapter. A listing of the file to generate the model is given in Appendix A.

C. COMPLEX FINITE ELEMENT MODEL OF LACE

1. Main Spacecraft Body

The on-orbit configuration of the LACE spacecraft is shown in Figure 8. From the figure, it can be seen that the LACE spacecraft consists of structural panels, solar panels, sensor panels, truss elements and various beam types.

The primary structure of LACE consists of a frame type structure consisting of channel section stringers, tee-section stringers, z-section doublers, and angle-section members. The primary structure also consists of honeycomb panels. Figures 9a and 9b show the basic configuration of the primary structure.

The secondary structure of the LACE spacecraft consists of the fixed and deployable solar array substrate, deployable sensor panels and deployable sensor arms. Figure 10 shows the LACE spacecraft secondary structure.

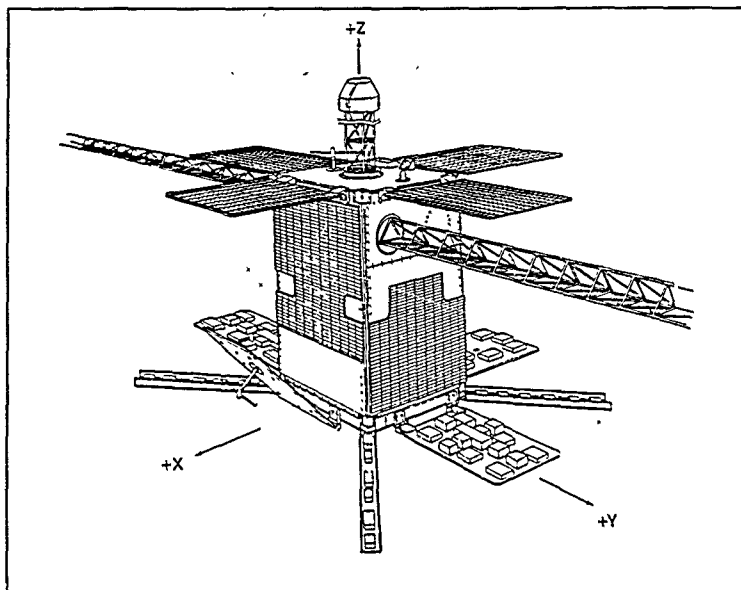


Figure 8. LACE Spacecraft On-Orbit Configuration

The primary frame members are made of aluminum, AL6061-T6. Table III shows the material characteristics of AL6061-T6 used in GIFTS.

Table III. AL6061-T6 CHARACTERISTICS

Yield Stress	1.8 E4 psi
Young's Modulus	9.9 E6 psi
Poisson's Ratio	.33
Mass Density	2.5382 E-4 lbs-sec ² /in ⁴

The honeycomb panels consist of .05 thick face sheets consisting of aluminum, AL6061-T6. The core of the panels are 1/4 -5052 -.003, with a density of .01552 lbs-sec²/in⁴.

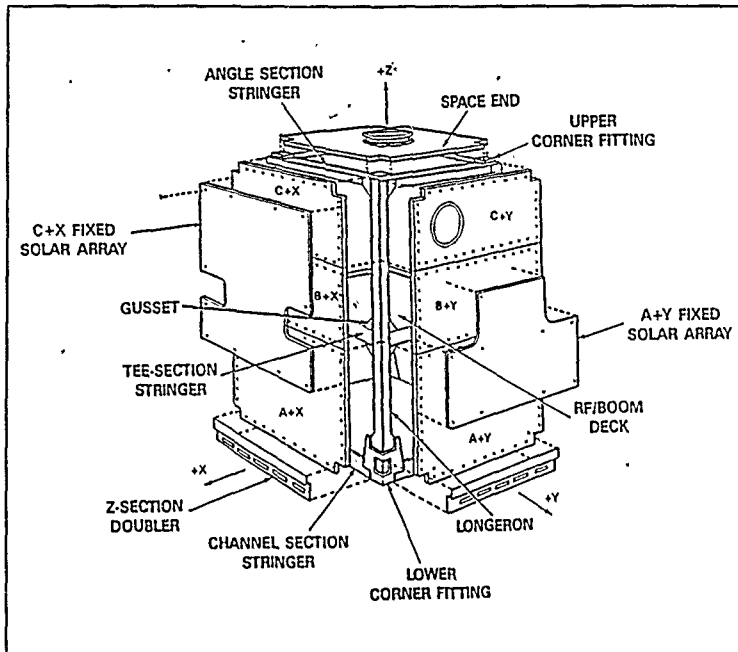


Figure 9a. LACE Spacecraft Primary Structure

Figures 11a and 11b show the primary and secondary honeycomb panel structure and dimensions.

The primary panels are one inch thick with a .9 inch core. The solar array panels are .5 inches thick with a .4 inch core and the deployable sensor panels are .75 inches thick with a core of .65. The deployable sensor arms are channel beams with .125 inch thick aluminum, AL6061-T6.

The honeycomb panels are modeled as aluminum panels, AL6061-T6, with appropriate conversions to account for

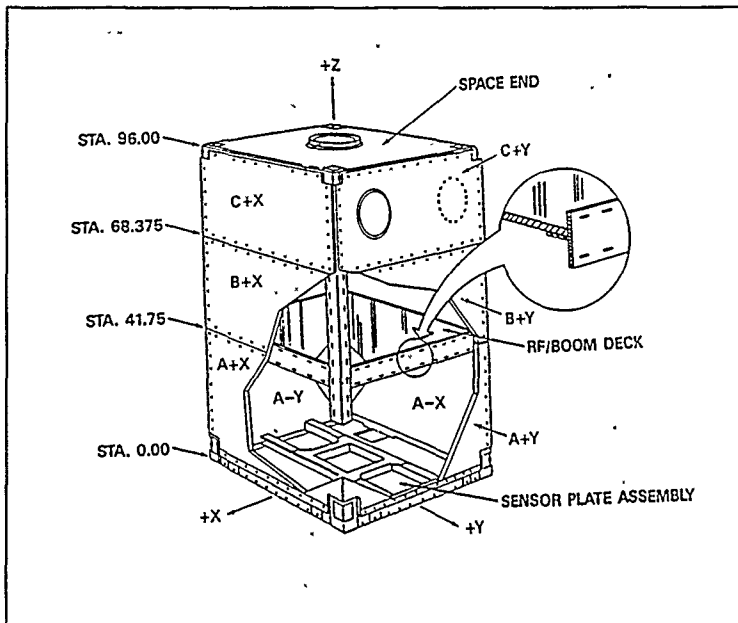


Figure 9b. LACE Spacecraft Available Panel Area

equivalent stiffness and weight. The panel stiffness for a honeycomb panel is given by [Ref. 11]

$$D = \frac{Eth^2}{2(1 - \nu^2)} \quad (42)$$

where

- E = Young's modulus
- t = face thickness of the panel
- h = core thickness
- ν = Poisson's ratio

The stiffness for each honeycomb panel is calculated using the above formula.

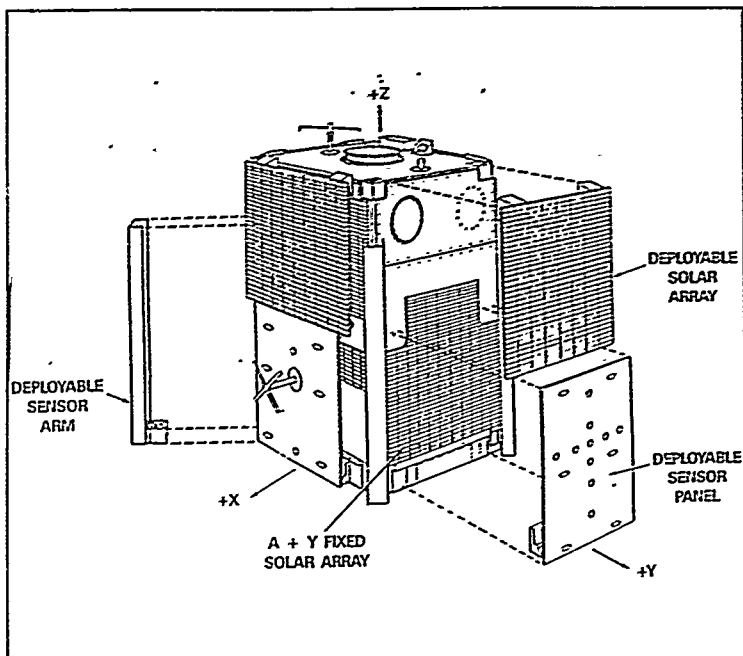


Figure 10. LACE Spacecraft Secondary Structure

Using the stiffness, an equivalent thickness is calculated, using the flexural rigidity formula for isotropic materials.

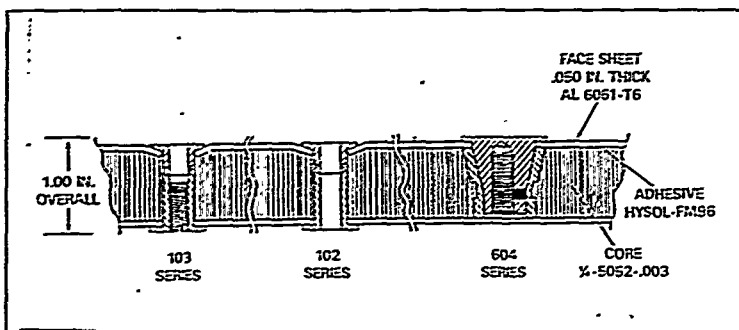


Figure 11a. Primary Panel

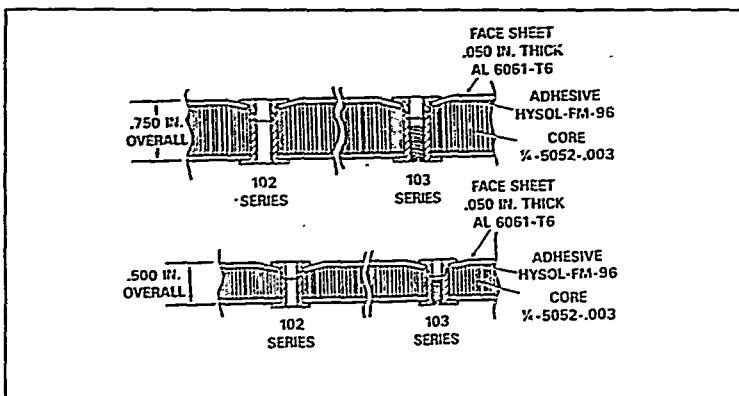


Figure 11b. Secondary Panels

$$D = \frac{E t^3}{12 (1-\nu^2)} \quad (43)$$

The mass of the honeycomb panels is computed and used with the new thickness to determine volume and density. These calculations are presented in Appendix B. Table IV summarizes

the new parameters used to model the honeycomb panels as aluminum panels with appropriate stiffness and mass.

Table IV. THICKNESS AND DENSITY PARAMETERS

	Thickness (in)	Density (lbs-sec ² /in ⁴)
Primary Panels	.624	5.364×10^{-5}
Solar Panels	.3634	8.1915×10^{-5}
Sensor Panels	.502	6.22×10^{-5}

The finite elements model of the main body of the LACE spacecraft is shown in Figure 12. The associated file to generate the model is given in Appendix C.

The LACE spacecraft has several sensors and components. Even though the spacecraft is essentially a rigid body, the mass of the components was modeled as accurately as possible according to the mesh size of the grids. Appendix D contains the component placements and mass distributions.

2. Spacecraft Trusses

The automatic deployable lattice booms are manufactured by AEC-Able Engineering Company, Inc. They are designed for applications that require high dimensional stability and high ratio of bending stiffness to weight. Figure 13 shows the principal parts of the continuous longeron boom and the retraction geometry. The longerons are continuous along the length and are connected to the batten frames with pivot fittings. Six diagonals provide shearing strength and stiffnesses. When the boom is twisted, tension increases on three of the diagonals, causing batten members to buckle and

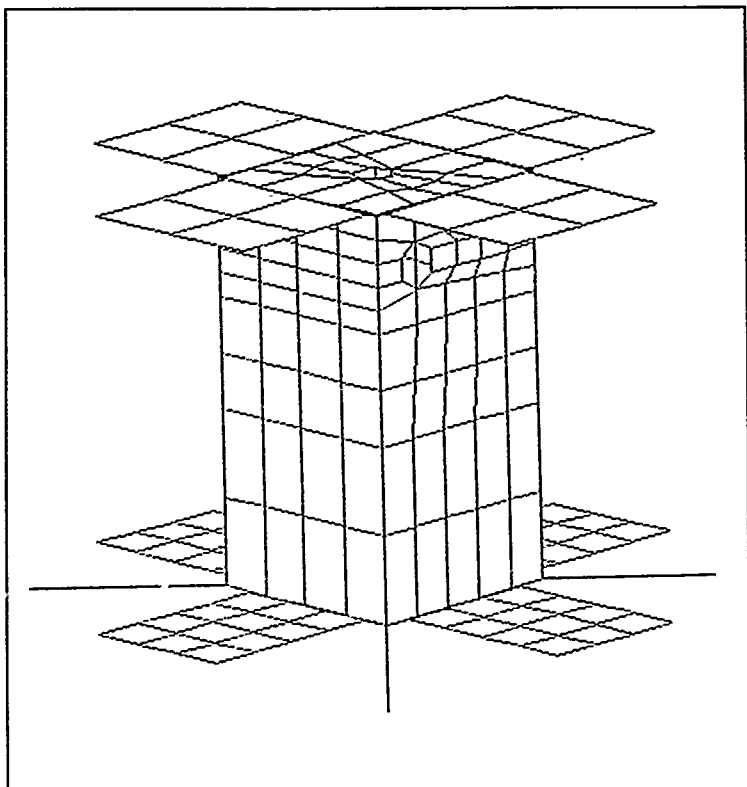


Figure 12. Finite Element Model of LACE Spacecraft

shorten. As twisting increases, the longerons rotate about the pivots and assume a helical configuration. In the retracted position the longerons are coiled in flat helices while battens lie on top of each other.

The longerons and battens are modeled as circular beams while the diagonals are modeled as rod elements. The battens

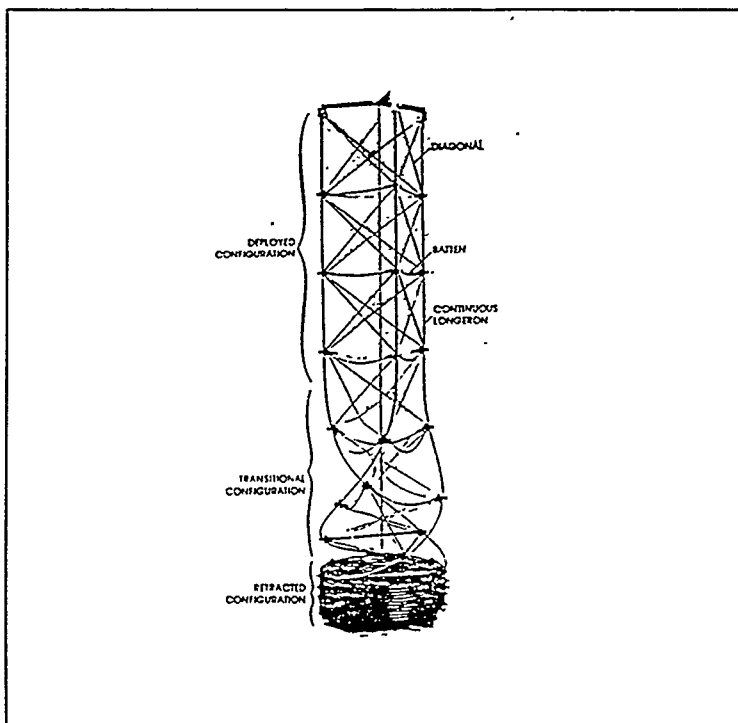


Figure 13. Continuous Longeron Boom

are oval-shaped and attached to the longeron by pivot joints, but for simplification the battens are modeled as circular and the joints are not modeled. Listed in Table V are the dimensions and properties of the truss. When fully retracted the triangular batten frames lie within a 10 inch diameter circle.

Figure 14 shows a cross-sectional view of the truss and its dimensions.

Table V. TRUSS PROPERTIES AND DIMENSIONS

Longeron and Batten Diameter	.150 inches
Diagonal Diameter	.050 inches
Material Type	S-glass epoxy
Density	.075 lbs/in ³
Young's Modulus	E=8.0 x 10 ⁶ psi

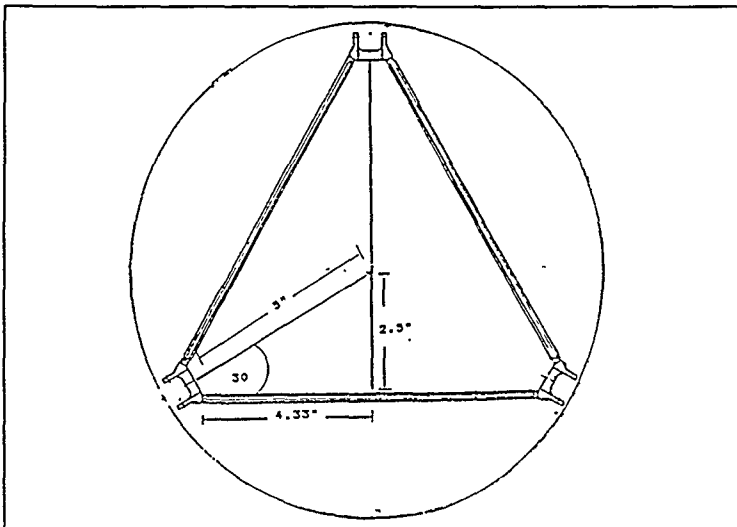


Figure 14. Cross-Sectional View and Dimensions of Longeron Structure

The booms of the spacecraft are ideal for substructuring. The 150-foot boom results in over 5,000 unknowns, when modeled as three-dimensional beam-truss elements. The substructuring technique is used in modeling when the number of unknowns may be reduced substantially. Initially, substructuring and multi-level substructuring

techniques were used to model the trusses, reducing the computational time considerably.

The first substructure was a 15-foot section of the truss. Ten of these substructures were joined together to construct the 150-foot boom. This multi-level substructure was attached to the main body of the spacecraft, thus forming a super element to the main body. This reduced the complete model from over 16,000 unknowns to about 2,500 unknowns. This was an attempt to capture the dynamics of the LACE spacecraft more accurately.

However, the use of substructuring generated large negative masses in the mass matrix. Kamel et al. [Ref. 12] provide a detailed formulation of the constrained substructuring techniques. As only the executable version of GIFTS program was available, and the objective was to obtain dynamic characteristics, it was decided to pursue modeling the whole structure.

The limitations of the program or the methodology adopted there is being pursued as well. The supplier of software is looking into the problem. The input files used to generate the multi-level substructuring model of LACE and typical negative mass elements are attached in Appendix E.

The listing of the file to create the trusses and attachment to the spacecraft is in Appendix F.

IV. RESULTS OF DYNAMIC ANALYSIS

For linear behavior, resonance occurs when the frequency of excitation equals the natural frequency. In order to avoid the ill-effects of large amplitude vibration at resonance, the natural frequency must be known and compared with potential excitation frequencies. The gravity gradient pitch vibration frequency is 2.3×10^{-4} Hz and is widely separated from the lowest modes of the finite element models.

Table V presents computed values for the first four modes of three different models of the LACE spacecraft.

Table V NATURAL FREQUENCIES OF THREE LACE MODELS

Mode	GIFTS Beam Model (Hz)	NASTRAN [Ref 1] Beam Model (Hz)	GIFTS Complex Model (Hz)
1	.01930	.01935	.0216
2	.04825	.04729	.0516
3	.05454	.0536	.0588
4	.1738	.1106	.1253

Initially, the NASTRAN beam model was developed by Naval Research Laboratories (NRL). The present beam model was developed as described in the previous chapter. The first three modes agree within 2%, however the present fourth mode appears to be an anomaly. The GIFTS complex model is consistently 10% higher than the NASTRAN model. The NASTRAN model appears to yield fairly good data in the lower modes.

This discrepancy may be attributed to the modeling uncertainties and approximation of the geometric and stiffness distributions. The detailed modeling of NASTRAN was not available. It may be noted that there is no excitation frequencies at those computed frequencies. Further, complex modeling is recommended when higher modes and frequencies are required. The simple model may not capture these higher modes and even skip some modes. The higher modes assume importance, especially, for very flexible structures and in the design of control systems for vibration control and suppression. Figures 15 to 20 show the mode shapes and frequencies for the NASTRAN model while Figures 21 to 26 show the data for the GIFTS beam model. Figures 27 to 30 show the GIFTS complex model of the spacecraft. Appendix F contains the frequency and mode shapes of the LACE spacecraft in three configurations as it deploys to its final state.

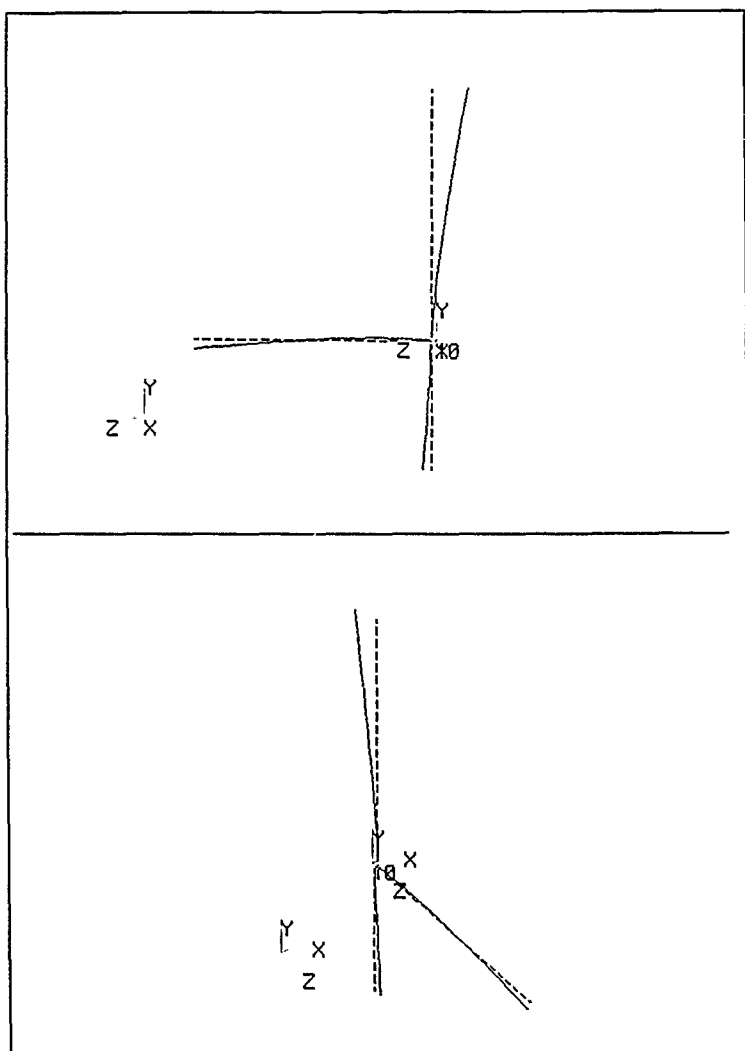


Figure 15. Mode 1, $\nu = .01935$ Hz, NASTRAN BEAM MODEL

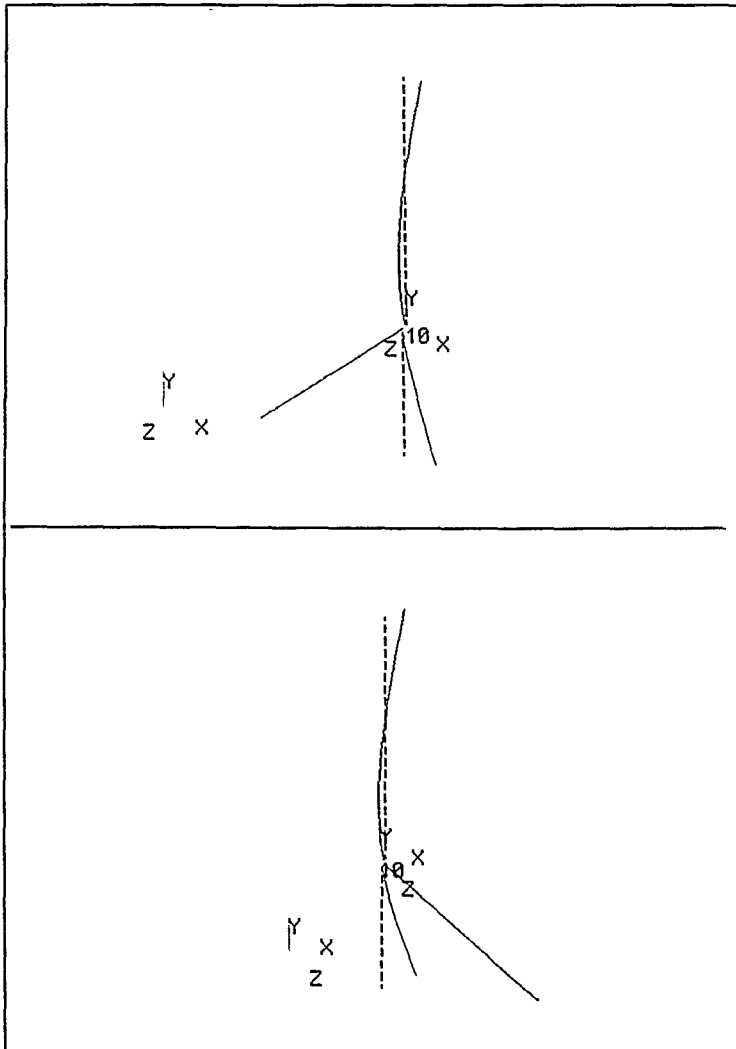


Figure 16. Mode 2, $\nu = .04729$ Hz, NASTRAN BEAM MODEL

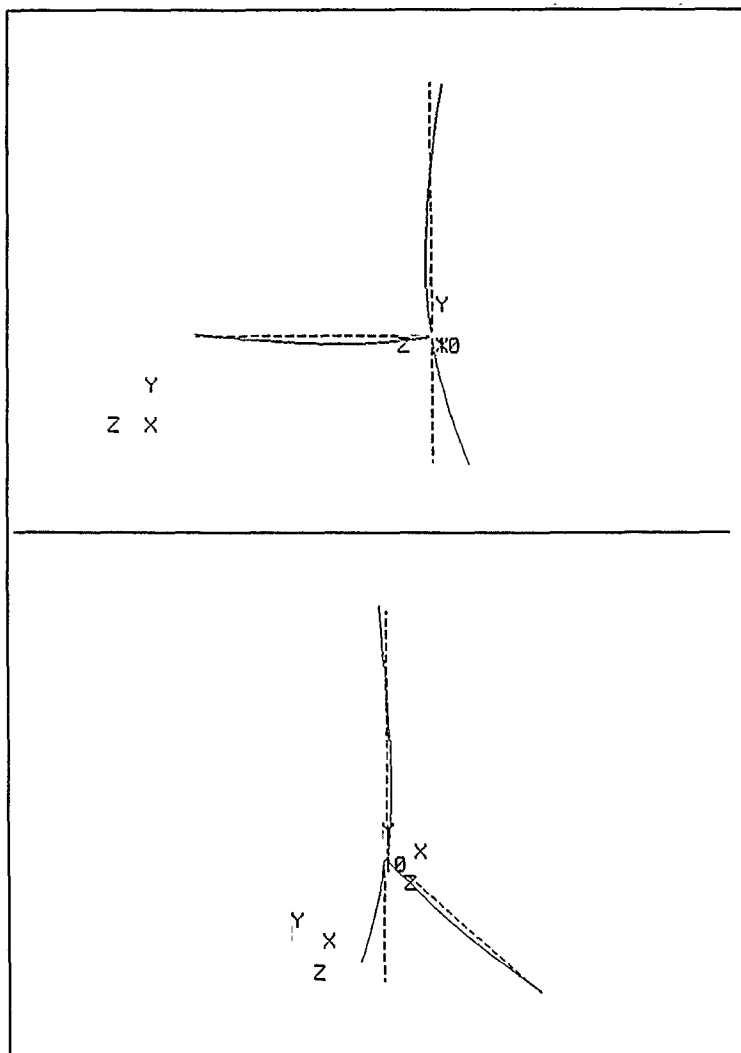


Figure 17. Mode 3, $\nu = .05362$ Hz, NASTRAN BEAM MODEL

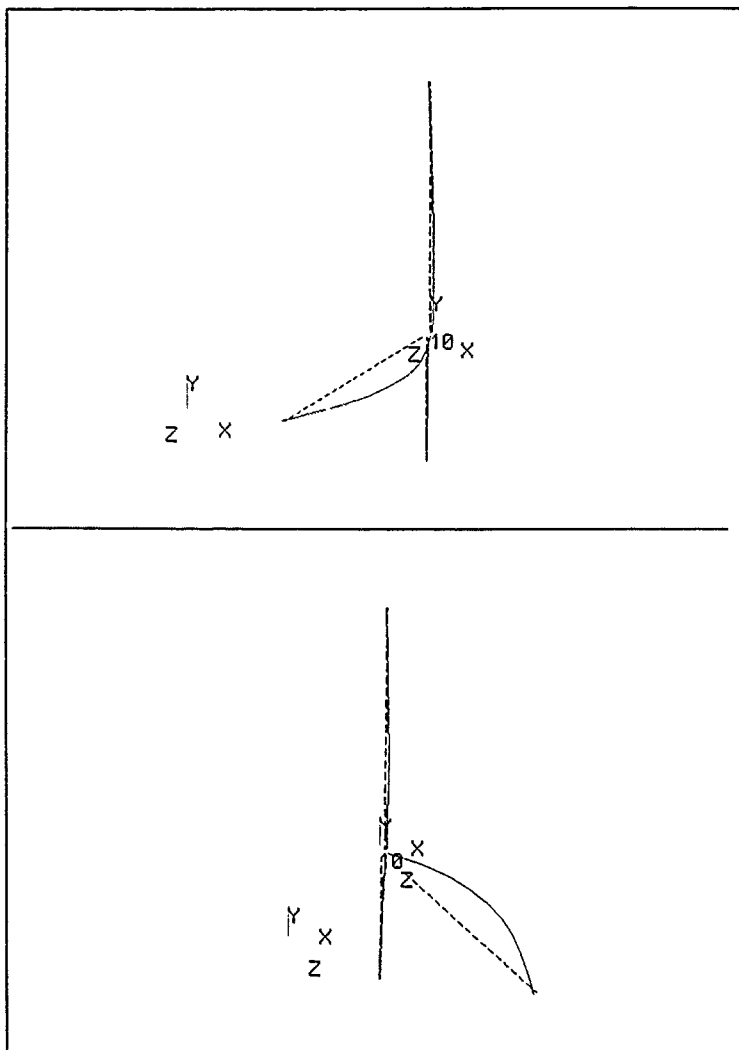


Figure 18. Mode 4, $\nu = .1104$ Hz, NASTRAN BEAM MODEL

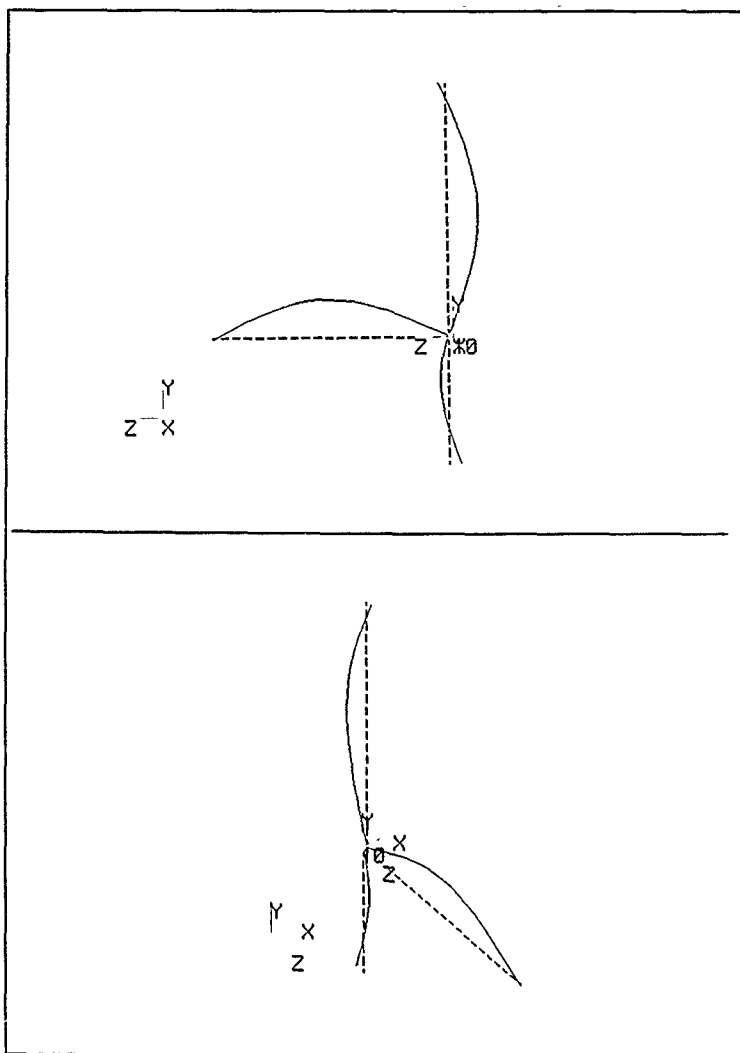


Figure 19. Mode 5, $\omega = .1808$ Hz, NASTRAN BEAM MODEL

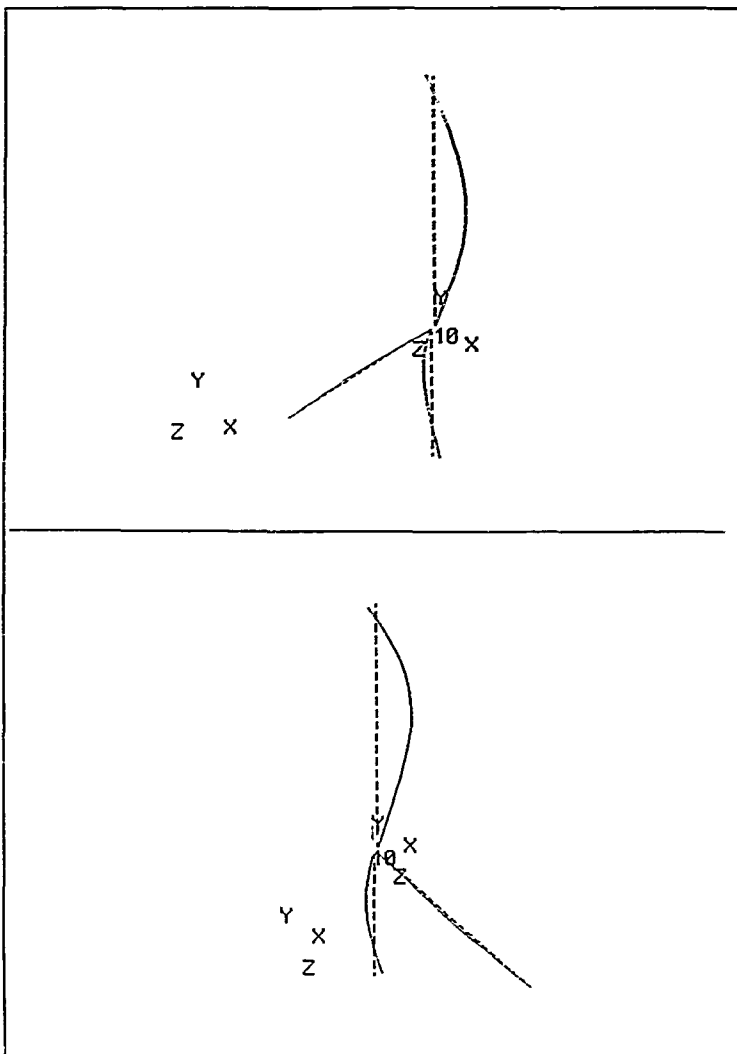


Figure 20. Mode 6, $\nu = .2019$ Hz, NASTRAN BEAM MODEL

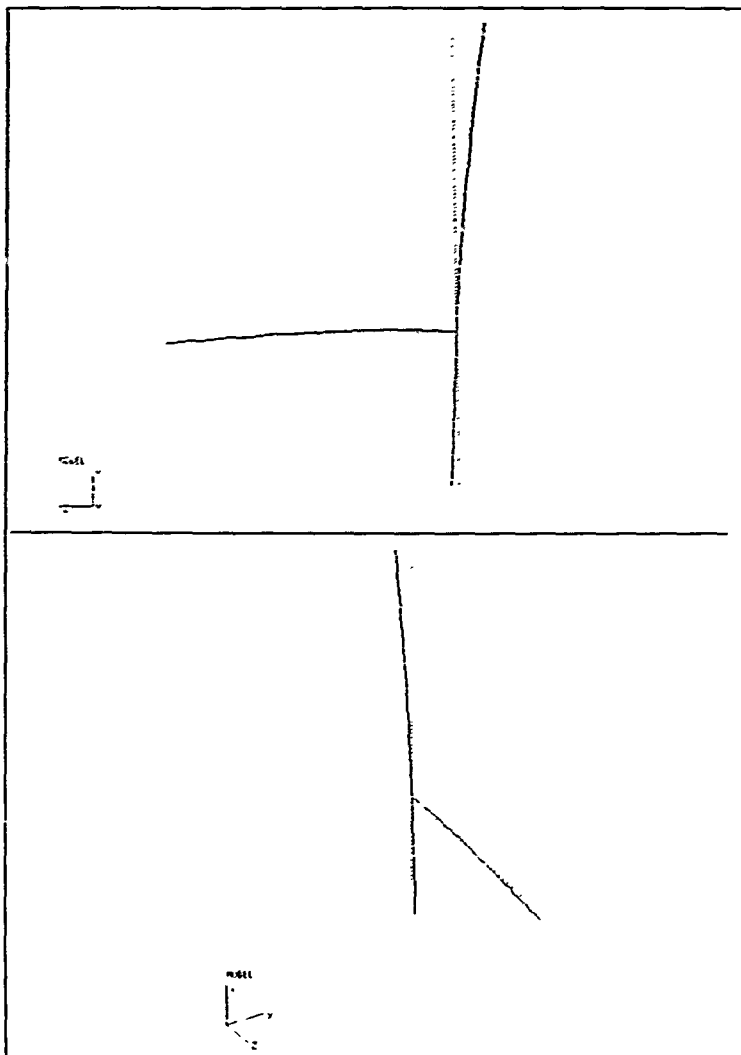


Figure 21. Mode 1, $\nu = .01930$ Hz, GIFTS BEAM MODEL

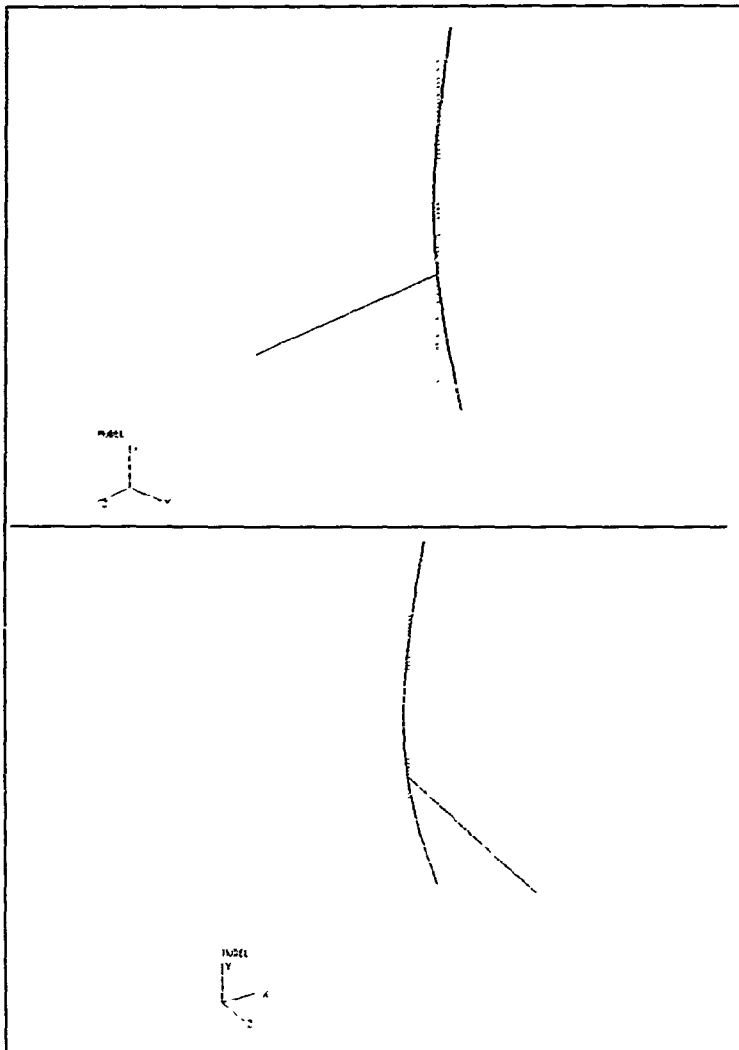


Figure 22. Mode 2, $\nu = .04825$ Hz, GIFTS BEAM MODEL

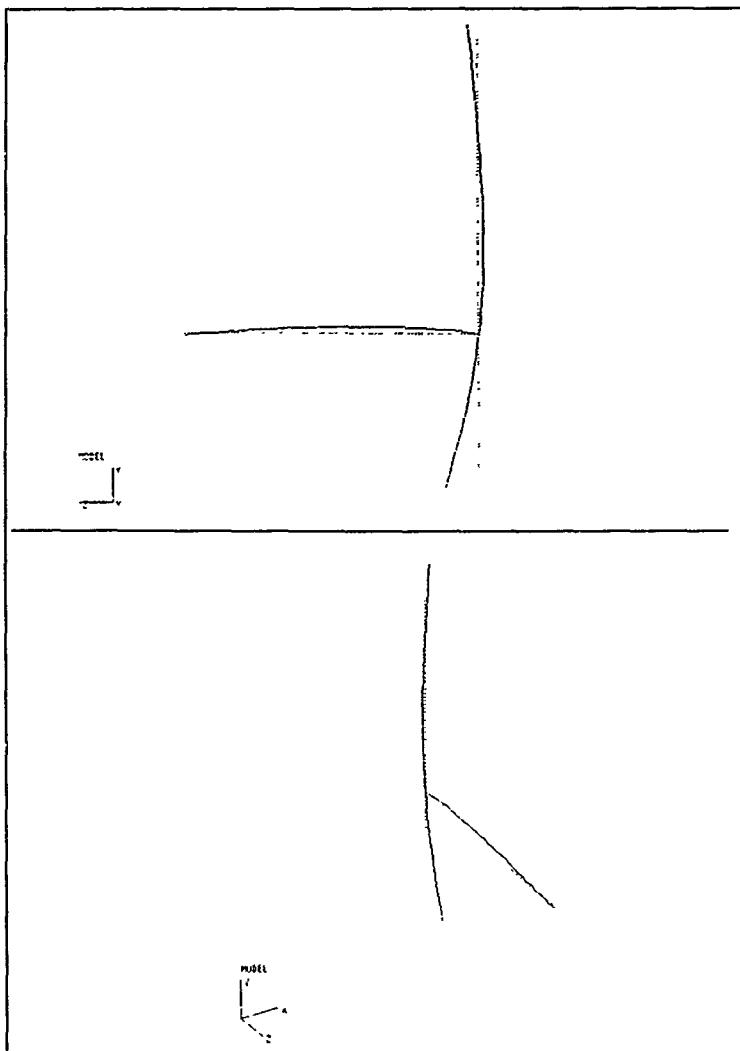


Figure 23. Mode 3, $\nu = .05459\text{E Hz}$, GIFTS BEAM MODEL

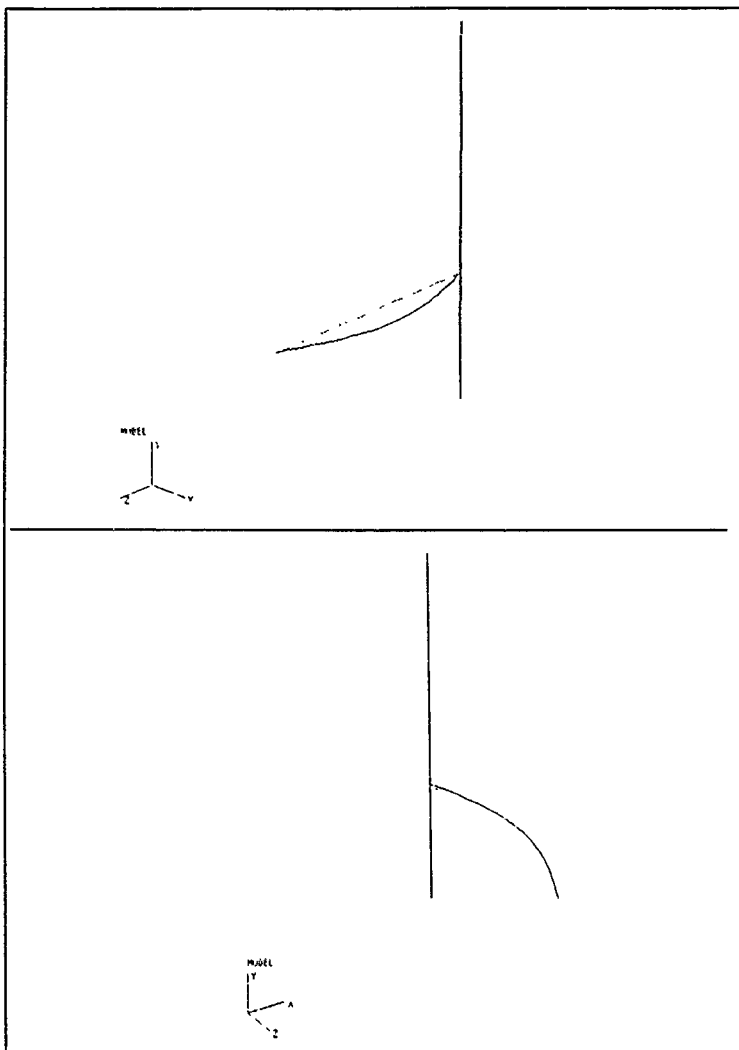


Figure 24. Mode 4, $\nu = .1738$ Hz, GIFTS BEAM MODEL

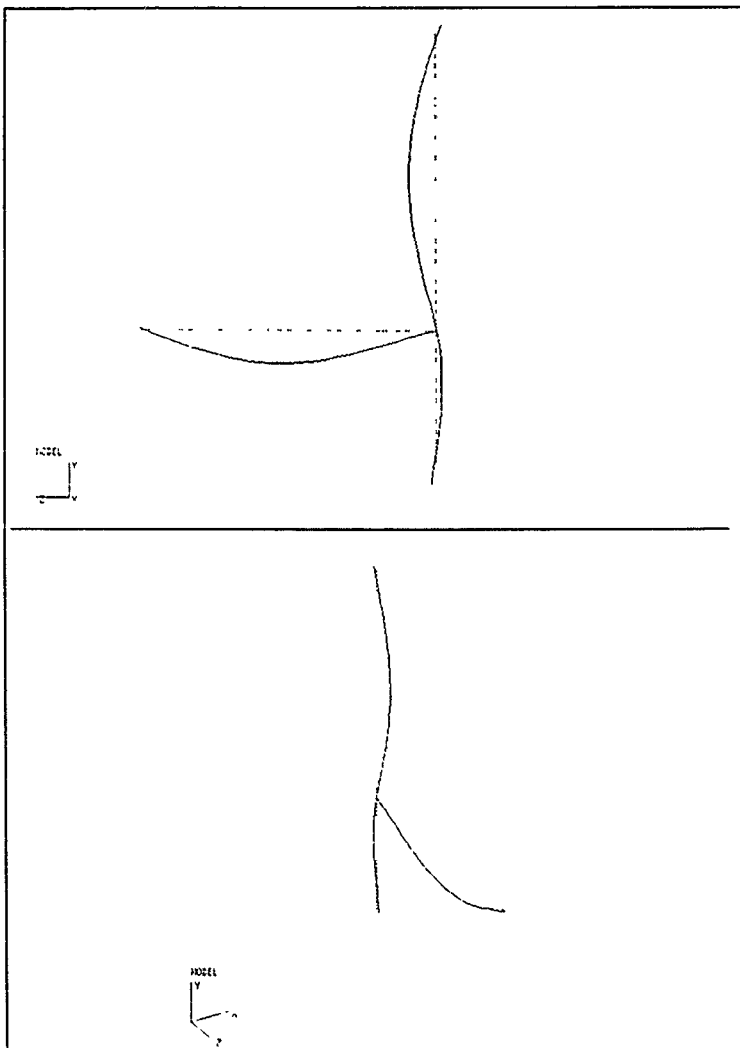


Figure 25. Mode 5, $\omega = .2142E$ Hz, GIFTS BEAM MODEL

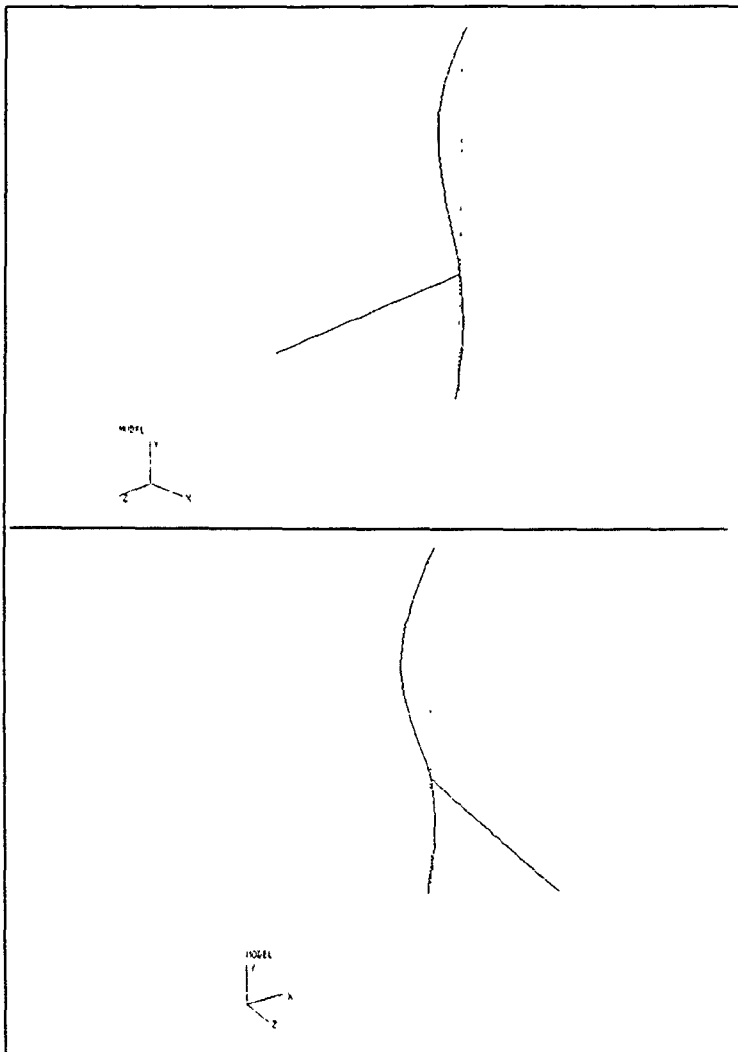


Figure 26. Mode 6, $\nu = .2349$ Hz, GIFTS BEAM MODEL

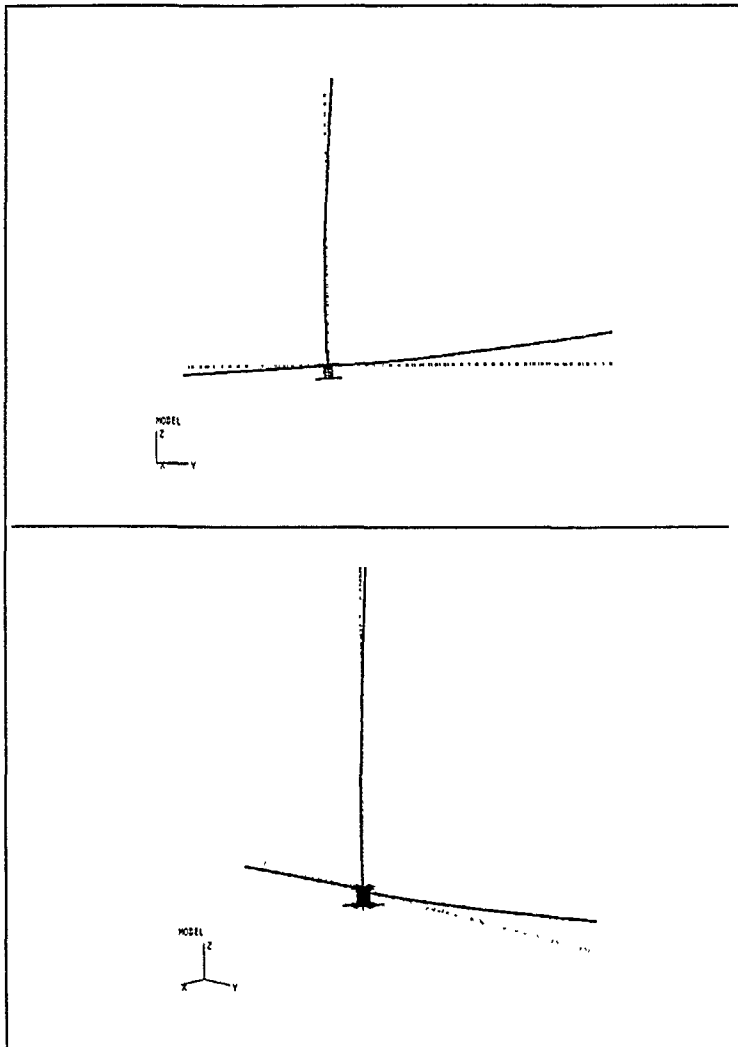


Figure 27. Mode 1, $\nu = .02163$ Hz, GIFTS COMPLEX MODEL

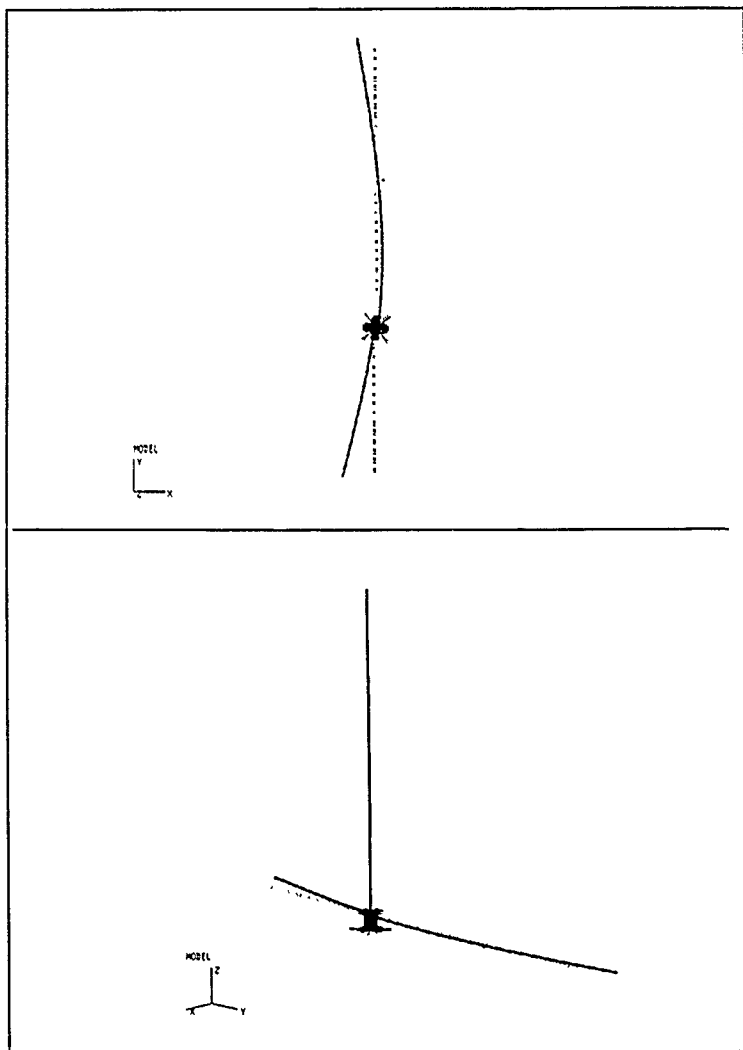


Figure 28. Mode 2, $\nu = .05165$ Hz, GIFTS COMPLEX MODEL

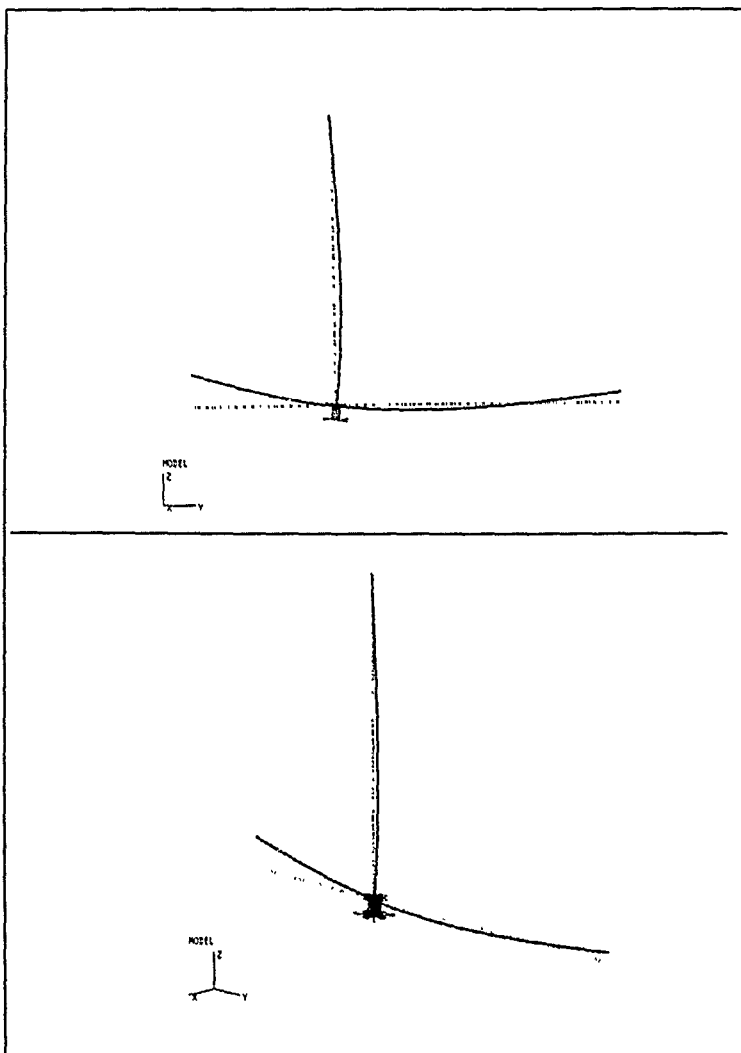


Figure 29. Mode 3, $\nu = .05879$ Hz, GIFTS COMPLEX MODEL

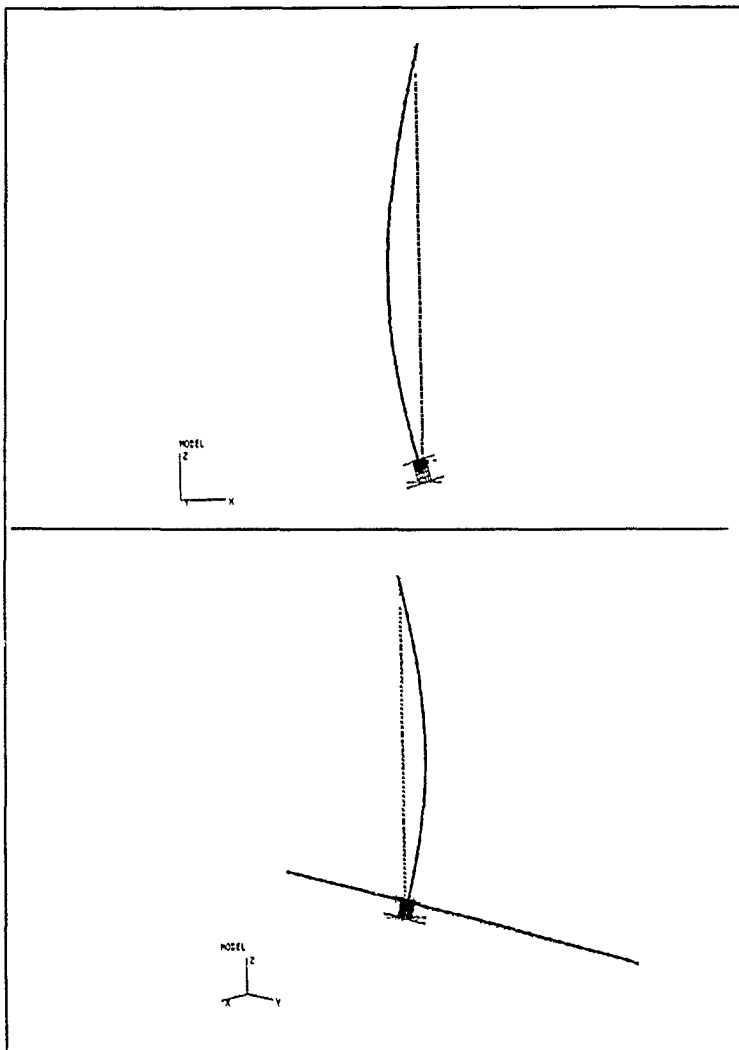


Figure 30. Mode 4, $\omega = .1253$ Hz, GIFTS COMPLEX MODEL

V. THERMOELASTIC EFFECTS

A change in temperature along a bar will change its dimensions. When an isotropic bar is heated uniformly and is free to expand, the sides will increase in length. The material undergoes a uniform thermal strain e , given by:

$$e_t = \alpha (\Delta T) \quad (44)$$

where α is the coefficient of thermal expansion and ΔT is an increase in temperature. The length of the bar will increase by an amount

$$\delta_t = \alpha (\Delta T) L$$

where L is the length of the bar.

The ABLE booms [Ref. 10] used on LACE are designed so that they undergo minimum thermal bending or twisting in the solar radiation environment. Pretwist is used to prevent thermal twisting or thermal bending that would occur if one longeron is shadowed by another.

This chapter presents analysis for deformations that could result in a worst case scenario. Two possible scenarios considered are when the boom may bend due to unequal heating of the diagonals and unequal heating of the longerons. Unequal heating of the diagonals is more likely to occur than unequal heating of longerons. [Ref. 13]. The following analysis

considers only the unequal heating of the diagonals and assumes no shadowing effects.

Sources of heat include spacecraft components, solar flux, albedo flux and thermal radiation of the earth. The solar flux is defined as the flux existing at a distance of one astronomical unit (AU) from the sun. Albedo flux is the fraction of total incident solar radiation on the earth which is reflected into space as a result of scattering in the atmosphere and reflection from the clouds and earth surfaces. Thermal radiation from the earth is the portion of incident solar radiation absorbed by earth and its atmosphere and re-emitted as thermal radiation according to Stefan-Boltzman law [Ref. 11]. For the computation of LACE thermal deformations, the following data is used [Ref. 13]:

Solar flux: 442 Btu/sq ft hr

Thermal Earth Radiation: 70 Btu/sq ft hr

Albedo flux: 160 Btu/sq ft hr

$$e/\alpha = .8$$

where e is the emissivity and α is the absorptivity.

The worst case of unequal diagonal heating occurs when the sun rays are parallel with one set of diagonals and almost perpendicular to the other set. The set of diagonals perpendicular to the sun will receive maximum solar flux. The parallel set will receive no solar flux, but will receive earth's albedo and thermal radiation flux. A simple approach is taken where the hottest and coldest temperatures of the

diagonals are calculated. This results in a maximum temperature of 192°F and a minimum of -5°F. Following the discussion in Ref. 12, calculations are carried out and presented in Appendix G.

It is assumed that the battens and longerons receive equal heating of 80°F. Using a 3-D model of the truss, the temperatures above, and a coefficient of thermal expansion of $1.75 \times 10^{-6}/^{\circ}\text{R}$, the maximum deflection is calculated. Figure 31a shows that the deformed shape is similar to the first bending mode. Figure 31b shows a closeup of the deformation. A maximum deflection of 1.88 inches is calculated using GIFTS. This is a 1.2% deformation for the 150 foot truss and should have negligible effect on the system dynamics.

However, thermal flutter could occur if the period of the thermal loading coincides with the natural frequencies of the spacecraft.

The first bending mode has a natural frequency of .02163 Hz. The thermal loading from the sun occurs over a long period and is on the order of 10^{-4} . The thermal loading is two orders of magnitude lower than the fundamental frequency and as a result should not interact with any natural frequencies.

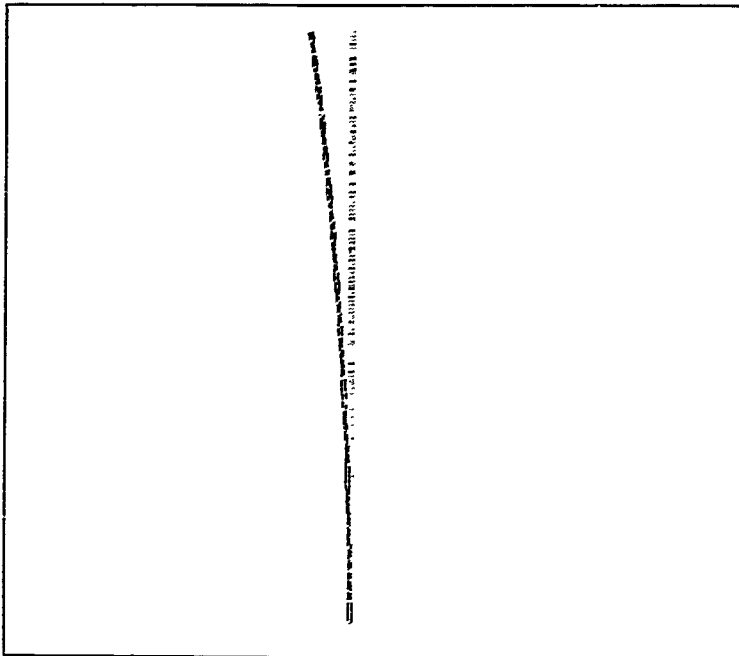


Figure 31a. Thermal elastic effects resemble 1st bending mode shape.

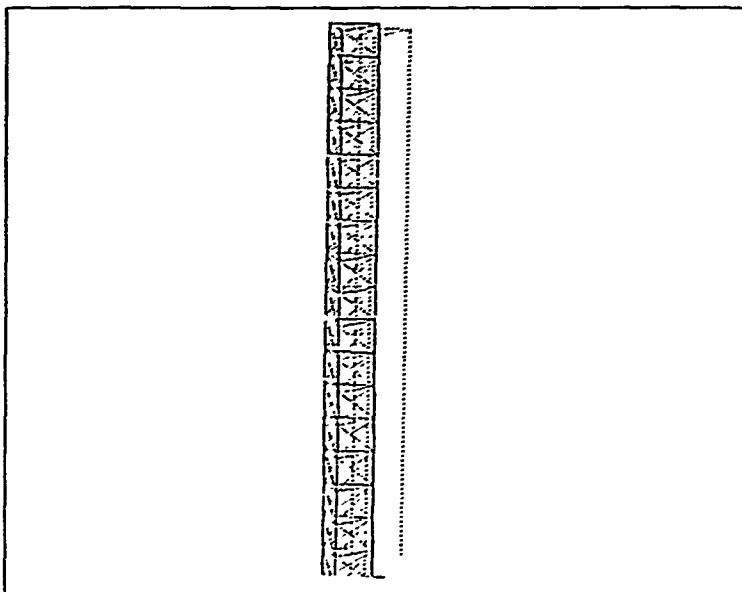


Figure 31b. Close-up view of thermoelastic effects

VI. MULTI-BODY DYNAMICS

A. COMPONENT MODE SYNTHESIS

In the previous chapter, finite element techniques were used to formulate a model of the LACE spacecraft for use in structural dynamics analysis. This section discusses a class of reduction methods known as component mode synthesis, or substructure coupling for dynamic analysis. These methods are useful for analysis of large structural dynamics problems.

The basic idea of component mode synthesis is to treat the complex structure as an assemblage of substructures. Each substructure is analyzed independently and then their dynamic characteristics (mode shapes and natural frequencies) are synthesized to analyze the complete structure. There are many variations of the method of component mode synthesis and extensive literature is available [Ref. 14, 15, 16, 17].

Hurty [Ref. 14] developed a procedure for analysis of structural systems using a displacement method which used three types of generalized coordinates, namely: 1) rigid body coordinates, 2) constraint coordinates, and 3) normal mode coordinates. Hurty used Rayleigh-Ritz approach in his formulation. The Craig-Bampton method [Ref. 15] is similar to the treatment due to Hurty, except that it simplifies the treatment of rigid-body modes of substructures by eliminating

the separation of boundary forces into statically determinate and statically indeterminate reactions [Ref. 15]. MacNeal [Ref. 16] introduced residual flexibility modes to retain the static contribution of a higher frequency truncated modes. Rubin [Ref. 17] developed a new method which adds residual inertial and dissipative results to the method introduced by MacNeal [Ref. 17].

This section will present the basics of component mode synthesis.

Craig [Ref. 18] provides a good overview of component mode synthesis methods. His notation and examples will be used extensively in this discussion.

A substructure is generally connected to one or more adjacent components and is composed of interior degrees of freedom and boundary degrees of freedom. Figure 32 illustrates a substructure connected to other components and shows boundary and interior coordinates.

The equation of motion for a component is given by

$$M\ddot{X} + C\dot{X} + KX = f \quad (45)$$

where M is the mass matrix, C is the damping matrix and K is the stiffness matrix.

The total set of physical coordinates of the component is defined as P, while interior and boundary points will be defined as I and B respectively. Boundary coordinates are further subdivided into statically determinate (rigid body)

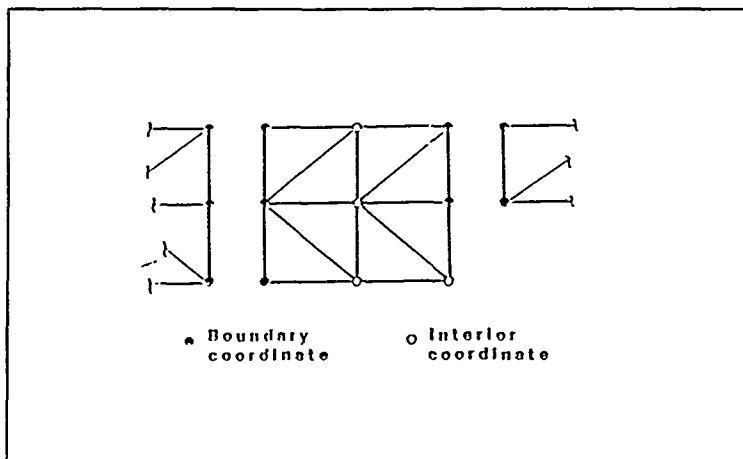


Figure 32. Unrestrained truss component

support of the component and its complement, redundant (excess) boundary coordinates designated as R and E respectively. These designations are used throughout this analysis.

Figure 33 shows a beam divided into several components and will be used to illustrate mode sets in the following discussion.

The two fundamental steps of component mode synthesis are to: 1) define component modes, and 2) to define coupling of components to form a system.

The physical coordinates, x , can be represented by component generalized coordinates, P by the transformation

$$X = \psi P \quad (46)$$

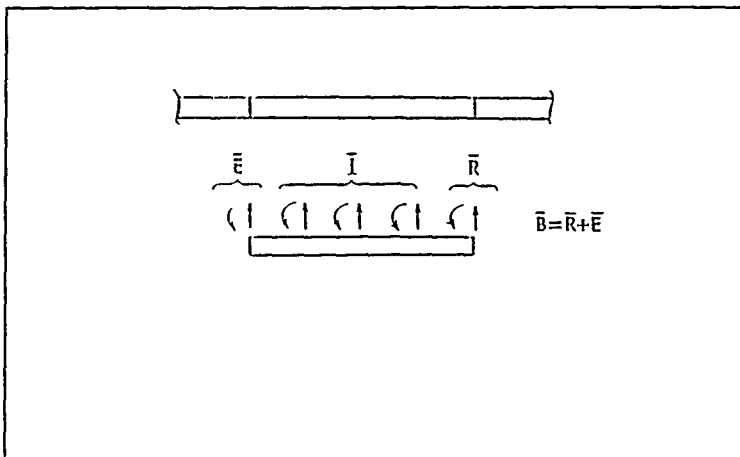


Figure 33. Beam model divided into components

where ψ consists of component modes of specified type [Ref. 14]. These include:

- normal modes of free vibration
- attachment modes
- constraint modes
- rigid body modes
- inertia relief modes

These modes are defined as follows. [Ref. 17]

1. Normal Modes

Normal modes are classified as fixed interface normal modes, free-interface normal modes or hybrid-interface normal modes depending on how the interface coordinates are restrained when the component normal modes are obtained using

$$(K - \omega_p^2 m) \phi_D = 0 \quad (47)$$

The modes are normalized with respect to the mass matrix m.

$$\phi_n^T m \phi_n = I_{nn} \quad \phi_n^T K \phi_n = \Lambda_{nn} = \text{diag}(\omega_p)^2$$

where ϕ_n is component normal modes. The notation ϕ will be used for normal modes, while ψ will be used for assumed modes.

2. Constraint Modes

A constraint mode is defined by statically imposing a unit displacement on one coordinate of a C set of physical coordinates. Let C=E and define a constraint mode by placing a unit displacement on one coordinate of the C set and zero displacement on the remaining C set. The matrix of constraint nodes, ψ_c is defined by the equation:

$$\begin{bmatrix} K_{II} & K_{Ic} & K_{Ir} \\ K_{cI} & K_{cc} & K_{cr} \\ K_{rI} & K_{rc} & K_{rr} \end{bmatrix} \begin{bmatrix} \psi_{Ic} \\ I_{cc} \\ O \end{bmatrix} = \begin{bmatrix} O \\ R_{cc} \\ R_{rc} \end{bmatrix} \quad (48)$$

This equation may be simplified to yield

$$\psi_c = \begin{bmatrix} \psi_{Ic} \\ I_{cc} \\ O \end{bmatrix} = \begin{bmatrix} -1 \\ -K_{II} & K_{Ic} \\ I_{cc} \\ O \end{bmatrix} \quad (49)$$

3. Attachment Modes

Attachment mode is defined by applying a unit force of the coordinates of an A set [Ref. 15]. In this case, attachment modes will be defined for A = E. The matrix of attachment modes ψ_a is shown by the equation

$$\begin{bmatrix} K_{ii} & K_{ia} & K_{ir} \\ K_{ai} & K_{aa} & K_{ar} \\ K_{ri} & K_{ra} & K_{rr} \end{bmatrix} \begin{bmatrix} \psi_{ia} \\ \psi_{aa} \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ I_{aa} \\ R_{ra} \end{bmatrix} \quad (50)$$

Using the first two rows of equation (50), ψ_a may be represented by

$$\psi_a = \begin{bmatrix} \psi_{ia} \\ \psi_{aa} \\ 0 \end{bmatrix} = \begin{bmatrix} g_{ia} \\ g_{aa} \\ 0 \end{bmatrix} \quad (51)$$

where $g = K^{-1}$ is the flexibility matrix.

4. Rigid Body Modes

The boundary conditions are depicted in Figure 45, where the R set will restrain the component from rigid body motion and the E set contains redundant boundary conditions. By defining the rigid body modes relative to the R set, the equation is given by

$$\begin{bmatrix} K_{ii} & K_{ie} & K_{ir} \\ K_{ei} & K_{ee} & K_{er} \\ K_{ri} & K_{re} & K_{rr} \end{bmatrix} \begin{bmatrix} \psi_{ir} \\ \psi_{er} \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad (52)$$

which simplifies to

$$\begin{bmatrix} K_{ii} & K_{ie} \\ K_{ei} & K_{ee} \end{bmatrix} \begin{bmatrix} \psi_{ir} \\ \psi_{er} \end{bmatrix} = - \begin{bmatrix} K_{ir} \\ K_{er} \end{bmatrix} \quad (53)$$

The ψ_r matrix is given by

$$\Psi_r = \begin{bmatrix} \Psi_{ir} \\ \Psi_{er} \\ I_{rr} \end{bmatrix} = \begin{bmatrix} g_{ii} & g_{ie} \\ g_{ei} & g_{ee} \end{bmatrix} \begin{bmatrix} K_{ir} \\ K_{er} \end{bmatrix} \quad (54)$$

5. Inertia-Relief Modes

This method defines attachment modes for a component with rigid body freedoms. This method was presented by Rubin [Ref. 16] and MacNeal [Ref. 17]. By letting D'Alembert force vectors associated with rigid-body modes be applied statically to a component which is fully constrained on the boundary, Ψ_m can be defined as follows.

$$\begin{bmatrix} K_{ii} & K_{ie} & K_{ir} \\ K_{ei} & K_{ee} & K_{er} \\ K_{ri} & K_{re} & K_{rr} \end{bmatrix} \begin{bmatrix} \Psi_{in} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} M_{ii} & M_{ie} & M_{ir} \\ M_{ei} & M_{ee} & M_{er} \\ M_{ri} & M_{re} & M_{rr} \end{bmatrix} \begin{bmatrix} \Psi_{ir} \\ \Psi_{er} \\ I_{rr} \end{bmatrix} + \begin{bmatrix} 0 \\ I_{er} \\ R_{rr} \end{bmatrix} \quad (55)$$

$$\Psi_n = \begin{bmatrix} \Psi_{in} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} K^{-1} (M_{ii}\Psi_{ir} = M_{ie}\Psi_{er} = M_{ir}) \\ 0 \\ 0 \end{bmatrix} \quad (56)$$

6. Coupling of Components

This section describes generalized substructure coupling as applied to free vibration analysis. [Ref. 18]

Assuming two components α and β having a common boundary interface, compatibility of interface displacement requires

$$x_b^\alpha = x_b^\beta \quad (57)$$

The interface forces are related by

$$\dot{x}_b^a = \dot{x}_b^b = 0 \quad (58)$$

By representing the physical coordinates x , by generalized coordinates p , the following equations are derived

$$x^a = \psi^a p^a, \quad x^b = \psi^b p^b \quad (59)$$

where ψ^a and ψ^b contain assumed static and dynamic modes.

The constraint equations can be written in generalized form to form a single constraint equation

$$CP = 0 \quad (60)$$

where

$$P = \begin{Bmatrix} p^a \\ p^b \end{Bmatrix} \quad (61)$$

Let P be rearranged and partitioned into dependent P_D and independent, P_I , coordinates. Then,

$$[C_{DD} C_{DI}] \begin{Bmatrix} p_D \\ p_I \end{Bmatrix} = 0 \quad (62)$$

where C_{dd} is nonsingular square matrix and equation

$$P = \begin{Bmatrix} p_D \\ p_I \end{Bmatrix} = \begin{bmatrix} -C_{DD}^{-1} C_{DI} \\ I_{II} \end{bmatrix} p_I = Sg \quad (63)$$

defines S and g , where

$$S = \begin{bmatrix} -C_{DD}^{-1} C_{DI} \\ I_{II} \end{bmatrix} \quad (64)$$

The μ and x corresponding to P are given by

$$\mu = \begin{bmatrix} \mu^a & 0 \\ 0 & \mu^b \end{bmatrix}, \quad x = \begin{bmatrix} x^a & 0 \\ 0 & x^b \end{bmatrix} \quad (65)$$

The coupled system of equations for an undamped system is given by

$$M\ddot{g} + K\dot{g} = 0 \quad (66)$$

where

$$M = S^T \mu S, \quad K = S^T x S \quad (67)$$

B. DYNAMICS OF FLEXIBLE BODIES IN TREE TOPOLOGY

1. Overview of Multibody Systems

Spacecraft and large spacecraft structures are typical multibody systems. Large strides have been made in the last 20 years in the efficient formulation and solution of multibody systems. Particular interest in multibody dynamics has risen in spacecraft dynamics. Initially, space vehicles were idealized as rigid bodies or elastic beams. In the mid-1980s equations of motion were published for a point-connected set of interconnected rigid bodies in a topological tree. A model containing rigid bodies and elastic appendages was developed in the 1970s. The next major step was the incorporation of body flexibility in the topological tree model. [Ref. 19]

2. Multibody Computer Program - TREETOPS

TREETOPS is a computer program developed to deal with multibody structures in an open-tree topology. It is a time

history simulation of a complex multibody flexible structure with active control elements. Some of the features include: 1) any or all bodies can be rigid or deformable, 2) hinges can have zero to six degrees of freedom, 3) the dimension of the problem equals the number of degrees of freedom, 4) individual body deformation can be described by any set of modal vectors, 5) an interactive program, and 6) extensive control simulation capability. [Ref. 18]

The computer simulation consists of three parts: defining a tree topology of flexible structures, define a controller and a set of sensors and actuators.

The structure of the TREETOPS model consists of bodies and hinges with sensors and actuators included for interfacing with the control system. Figure 34 shows a typical structure.

a. Body Types

The program simulates a set of bodies in a tree topology. Each body is defined independently. Sensors, actuators and hinges are connected to specific points called node points. Each body may be defined as rigid or flexible.

Each body is to be defined with an ID number, mass properties, center of mass and all its pertinent node points. [Ref. 20]

b. Hinges

Hinges interconnect two adjacent bodies. One body is called the inboard body and the other is called the outboard body. The inboard body is the one on the side closest

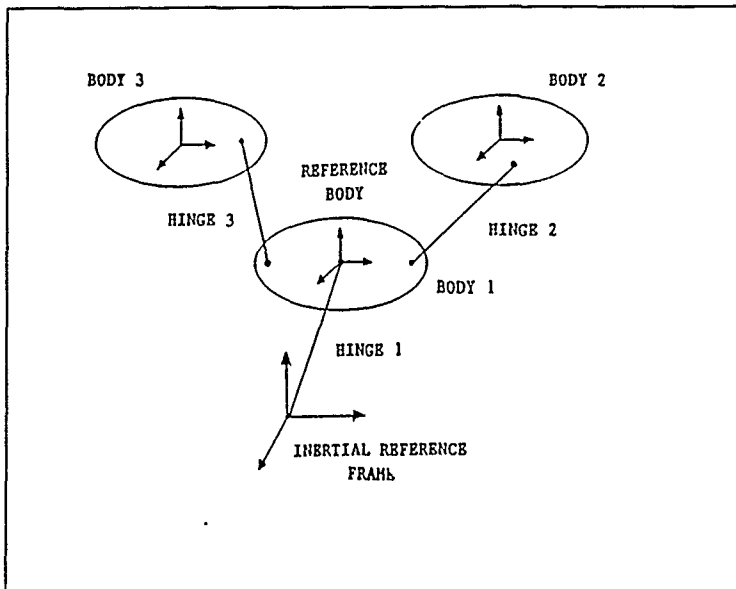


Figure 34. Structure composed of bodies and hinges

to the inertial reference frame. Figure 35 shows a hinge representation.

The functions of the TREETOP hinges are to [Ref.20]:

1. define topology of the structure
2. define kinematic variables of the multibody system
3. define relative orientation between adjacent bodies.

c. Sensors and Actuators

A set of 16 sensors have been built into the simulation. They include rate gyros, resolvers,

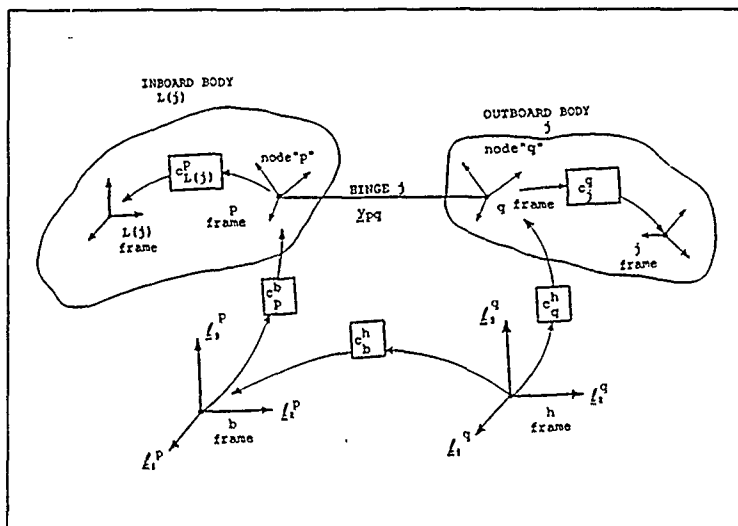


Figure 35. General representation of j th hinge

accelerometers, position and velocity sensors, tachometer, sun and star sensors, etc. The actuators serve as a way to apply force and torque inputs. Inputs may be control or disturbance inputs. Disturbance inputs can be applied with function generators to the actuators. Actuator types include reaction jets, hydraulic cylinder, moment actuator and torque motor.

d. Orbit Environment

TREETOPS has the capability to model the orbit environment of a spacecraft to include gravity gradient and aerodynamic drag. A magnetic field model is included which produces a force through interaction with magnetic actuators. In computing the atmospheric drag, TREETOPS uses atmospheric

density computed from the JACCHIA 1970 atmospheric model. The spacecraft orbit is determined by entering the six orbital parameters.

VII. CHAOTIC VIBRATIONS

A. HOW TO IDENTIFY CHAOTIC VIBRATIONS

Chaos is defined as a motion that is sensitive to initial conditions [Ref. 21]. Chaos can occur only in nonlinear systems, but all nonlinear systems do not exhibit chaos. Chaos can be observed in many physical systems. A partial list is shown:

1. Vibrations of buckled elastic structures
2. Mechanical systems with play
3. Large, three-dimensional vibrations of structures
4. Aeroelastic problems
5. Systems with sliding friction
6. Feedback control devices

In order to identify chaotic motions, several procedures are suggested [Ref. 21], such as

1. Identify nonlinear elements in the system
2. Check for sources of random input in the system
3. Observe time history of the measured signal
4. Observe phase plane history
5. Examine Fourier spectrum of the signal
6. Determine Poincaré map of the signal
7. Vary system parameters

Quantitative characteristics of chaotic vibrations and the diagnostic tools used are summarized as follows:

1. Sensitivity to changes in initial conditions (Lyapunov exponent and fractal basin boundaries)
2. Broad band spectrum of Fourier transform when motion is generated by a single frequency
3. Fractal properties of the motion in phase space which indicate a strange attractor (Poincaré maps, fractal dimension)
4. Increasing complexity of regular motions as experimental parameters are changed
5. Transient or intermittent chaotic motions; nonperiodic bursts of irregular motion or initially random-like motion that settles into regular motion.

1. Nonlinear System Elements

A linear system does not exhibit chaotic vibrations. Typical nonlinear effects from mechanical systems include nonlinear stiffness, material nonlinearity, nonlinear damping, free-play, and nonlinear boundary conditions. Nonlinear elastic effects can be due to large deformation. A good example of material nonlinearity is the stress-strain relations of materials modeling rubber or elastomers.

2. Random Inputs

There are no assumed random inputs in chaotic vibrations. Applied forces and excitations are assumed to be deterministic. By definition, chaotic vibrations arise from deterministic physical systems. A large output signal to input noise ratio is required if nonperiodic response is to be attributed to a deterministic system behavior. [Ref. 21]

3. Observation of Time History

The first indication of chaos may be indicated in the time history. The motion observed shows no visible pattern or periodicity and may be chaotic or random.

This method is not conclusive, since motion could have a long-period behavior that is not detected or quasiperiodic motion where two or more periodic signals are present.

4. Fourier Spectrum

The presence of a broad band Fourier spectrum in the output is another clue that may be used to suspect chaotic vibrations. A precursor to chaos is the presence of ω_0/n subharmonics. However, multiharmonic outputs do not always imply chaotic vibrations as hidden degrees of freedom may be present.

5. Phase Plane History

In the phase plane, complete information about a dynamical system is represented by a point. At the next point in time when the system dynamics change, the point is displaced.

This moving point gives the history of the dynamical system. The coordinates chosen for the study of dynamics, typically, are the amplitude and velocity of motion. Figure 36 shows the phase plane of a simple pendulum. The circle on the phase plane represents the motion over one cycle and is called the trajectory. It should be noted that a periodic motion is a closed orbit in the phase plane and is called a limit cycle.

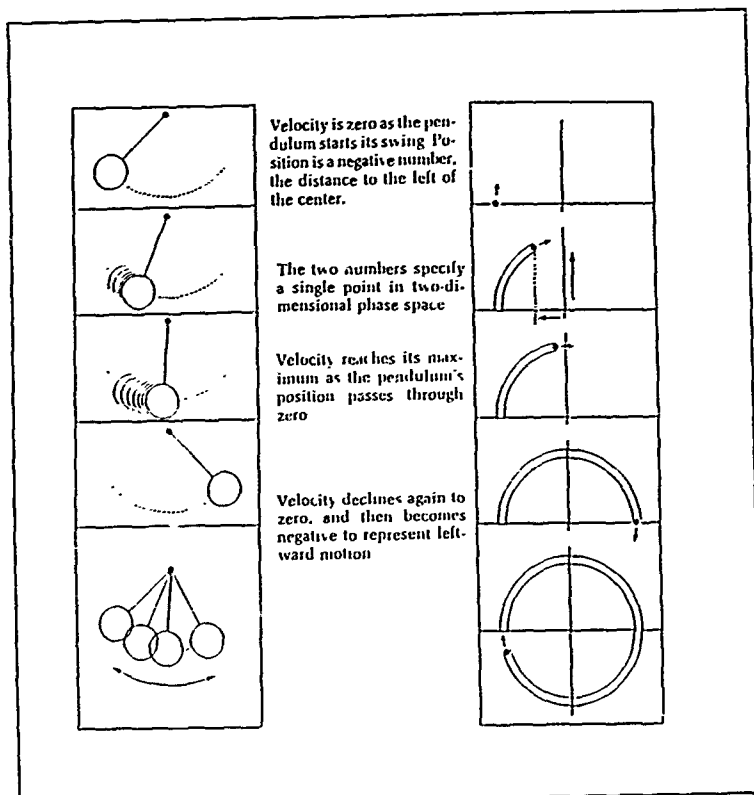


Figure 36. Phase plane of a pendulum [Ref. 21]

Chaotic motions have orbits that never close or repeat. As a result, the trajectory of the orbits will tend to fill up the phase plane.

6. Pseudo-Phase-Space Method

This method is used when only one variable is available, as in typical flight tests where measurements are from a strain-gage or accelerometer. In order to do the 2-D phase plot from strain-gage measurements, the signal must be differentiated. In the case of accelerometer data, the signal has to be integrated twice.

However, by integrating or differentiating, the signal is filtered [Ref. 22]. Differentiating the signal will amplify high frequencies and attenuate low frequencies. Integration will have an opposite effect. As a result, phase plane plots obtained from experimental data will be inaccurate. This resulted in the development of the pseudo-phase-space method or embedding space method. For a one degree system with a measurement $x(t)$, the signal is plotted against itself but delayed or advanced by a fixed time constant: $[x(t), x(t+T)]$. This plot yields properties similar to the classical phase plane. The closed trajectory in the classical phase plot will be closed in the pseudo-phase method and chaotic motion appear chaotic in both phase planes.

When the state variables are greater than three (position, velocity, time), higher dimension pseudo-phase-space may be constructed using multiple time delays, i.e., $(x(t), x(t+T), x(t+2T))$.

The advantage of the pseudo-phase plane method is that a single observable variable can be used to construct the

pseudo phase picture and portray the system dynamics without distorting the response through integration or differentiation.

7. Poincaré Section

The Poincaré section can be constructed by placing a two-dimensional surface in a three-dimensional phase space and noting where the points of the trajectory penetrate this surface. This slice will reveal the internal structure of this location.

If the Poincaré section does not consist of a finite set of points or a closed orbit, the motion may be chaotic. For some lightly damped systems, the Poincaré section of chaotic motion appears as a set of unorganized points. This motion is called stochastic and is shown in Figure 37a. In damped systems, the Poincaré section appears more organized with parallel lines as shown in Figures 37b and 37c. The Poincaré sections can be enlarged to observe further structure (Figure 38). After several enlargements, if the structured sets continue to exist, the motion is defined as a strange attractor. This embedding of structure within the structure indicates fractal nature of the behavior, which is a strong indicator of chaotic motions.

B. QUANTITATIVE TESTS FOR CHAOS

The previous section summarized qualitative methods that require experience to evaluate chaotic systems. There are some

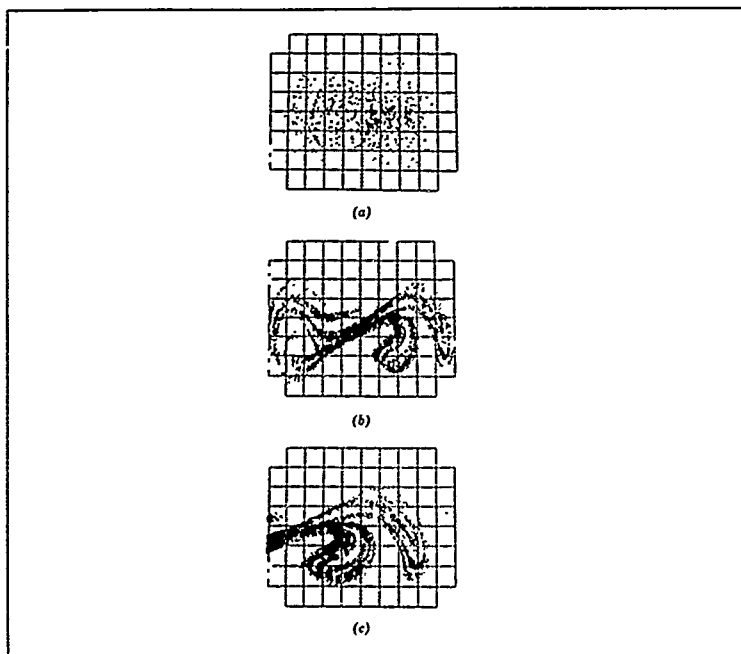


Figure 37. Poincaré maps chaotic motion

quantitative measures to study chaotic motions. Two well-known methods are the Lyapunov exponent and fractal dimension [Refs. 22, 25]. These methods are described below. The Lyapunov exponent will not be used in this analysis and will be discussed summarily.

1. Lyapunov Exponent

The Lyapunov exponent measures how sensitive the system is to changes in initial conditions. It measures the exponential attraction or separation, of two adjacent

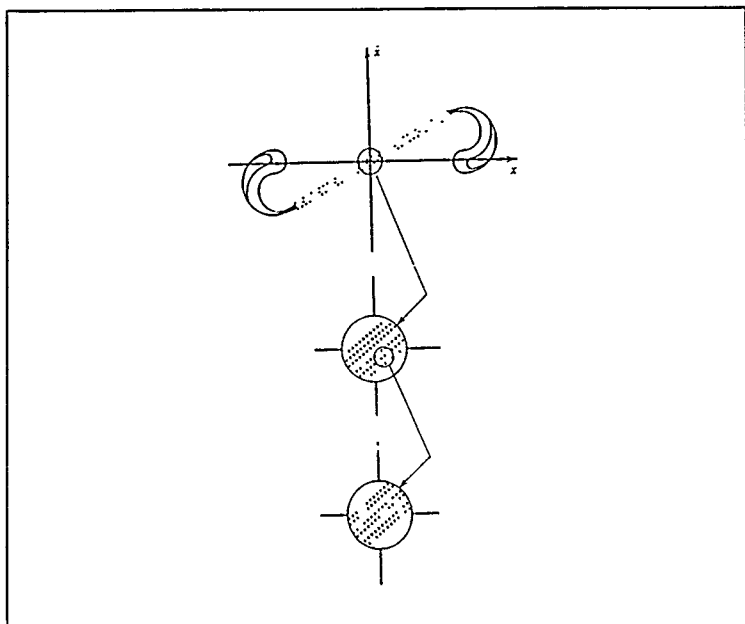


Figure 38. Poincaré map of chaotic vibration

trajectories in phase space with different initial conditions.

It is defined as

$$d(t) = d^{2LT} \quad (68)$$

or

$$L = \log_2 \left(\frac{d(t)}{d} \right) \quad (69)$$

where d is the initial distance between two trajectories.

$d(t)$ is the distance at a later time.

L is the Lyapunov exponent.

A positive exponent implies $d(t)$, the later distance will be larger than the initial distance and indicates chaotic dynamics.

2. Fractal Dimension

The fractal dimension is another quantitative test for chaos and gives a lower bound on the number of essential variables needed to model the dynamics of the system. Non-integer values for a fractal dimension indicates presence of a strange attractor. [Refs. 22,25]

There are six ways to classify fractal dimensions. The dimension that will be discussed in this analysis is the correlation fractal dimension.

The correlation fractal dimension is defined as

$$C(r) = r^d \quad (70)$$

where: $C(r)$ is the probability of the attractor within a circle, sphere or hypersphere of radius r , and d is the fractal dimension.

By taking the natural logarithm of both sides of equation (70) and solving for d , following equation results:

$$d = \lim_{r \rightarrow 0} \left(\frac{\ln C(r)}{\ln r} \right) \quad (71)$$

The procedure adapted in Sarigul-Klijn [Ref. 22] is described below:

1. Start with a point on the attractor and calculate the number of points inside a circle of radius r .

2. Calculate probability $C(r)$ by dividing this number of points by total number of points in the attractor.
3. Repeat this for several points along the attractor.
4. Compute $C(r)$ for several values of r .
5. The slope of $\log (C(r))$ versus $\log (r)$ gives d , the correlation fractal dimension.

To obtain the correlation dimension of the attractor of a given system, the procedure must be applied in the pseudo phase space for several embedded dimensions. The asymptotic value of the correlation dimension is the fractal dimension of the attractor and is given by

$$C(r) = \lim_{N \rightarrow \infty} \frac{1}{N^2} \sum_i^N \sum_j^N H(r - |x_i - x_j|) \quad (72)$$

where: $H(s) = 1$ if $s > 0$ and $H(s) = 0$ if $s < 0$.

$|x_i - x_j|$ is the Euclidean distance between the points.

N is total number of points.

If the fractal dimension is approximately equal to the phase space used for the calculation, the attractor lies in a higher dimensional phase space. If the fractal dimension is non-integer and is independent of the dimension of phase space, the signal is characterized as chaotic. [Ref. 22]

C. LACE SPACECRAFT BOOM AS A NONLINEAR SYSTEM

The booms for the LACE spacecraft have a constant EI distribution [Ref. 10] and the response would appear to be linear. However, at each bay, battens are joined to the

longerons by joints. Freeplay introduced at the joints tend to introduce nonlinearities. In this section, the spacecraft boom alone is modeled and a parametric study to simulate the influence of nonlinearities introduced by the freeplay at the joints on the system response is presented. The resulting behavior of the motion is studied using the methods of chaos [Ref. 21].

The LACE spacecraft boom is modeled as a nonlinear single-degree of freedom system. The equation of motion for such a system is described by

$$m\ddot{u} + f(u, \dot{u}, t) = A_0 \cos \omega t \quad (73)$$

where $f(u, \dot{u}, t)$ contains nonlinear damping and stiffness terms. The stiffness of the boom is modeled as

$$f_{si} = A_1 u^3 + B_1 \dot{u}^2 + C_1 \dot{u} + d_1$$

and the damping as

$$f_{dl} = A_2 \dot{u}^3 + B_2 \dot{u} + C_2$$

For the present analysis, the damping is assumed to be linear and contains only the linear term corresponding to equivalent viscous damping. The nonlinear stiffness contribution due to the joints is modeled by the cubic term, $A_1 u^3$. The linear term representing the boom stiffness distribution is determined from the experimental stiffness properties of the beam using the relation

$$K = \frac{12EI}{L^3} \quad (74)$$

The coefficient for the cubic term is treated as a parameter and as part of the parametric study, is varied as a function of the linear term as follows

$$A_1 = C_1 + nC_1 \quad (75)$$

where n varies from ± 1 to ± 5 . The equation of motion reduces to Duffing's equation in the following form:

$$m\ddot{u} + B_2\dot{u} + A_1u^3 + C_1u = A_0\cos\omega t \quad (76)$$

The response of this nonlinear system to a forcing function is determined by approximating the derivatives as shown in the equation of motion. A solution based on step-by-step integration is used to generate the time response. A FORTRAN program was developed based on the "linear acceleration method" and is presented in Appendix I. The recursion formulas used for the numerical integration is derived in the following analysis.

In the linear acceleration method adopted here, the acceleration is approximated for a given step by the following relation:

$$\ddot{u}(\tau) = \ddot{u}_i + \frac{\Delta \ddot{u}_i}{\Delta t} \tau \quad (77)$$

Integration of equation (77) yields

$$\dot{u}_{i+1} = \dot{u}_i + \ddot{u}_i \tau + \frac{(\Delta \ddot{u}_i) \tau^2}{2} \quad (78)$$

and

$$u_{i+1} = u_i + \dot{u}_i \tau + \ddot{u}_i \frac{\tau^2}{2} + \frac{\Delta \ddot{u}_i \tau^3}{6} \quad (79)$$

By using incremental quantities, Δp_i , Δu_i , $\Delta \dot{u}_i$, and $\Delta \ddot{u}_i$, the computational algorithm is set up. Equation (79) may be solved for \dot{u}_i and equations (78) and (79) are combined to give $\Delta \dot{u}_i$ as follows:

$$\Delta \dot{u}_i = \frac{6}{\Delta t^2} \Delta u_i - \frac{6}{\Delta t} \dot{u}_i - 3 \ddot{u}_i \quad (80)$$

$$\Delta \dot{u}_i = \frac{3}{\Delta t} \Delta u_i - 3 \dot{u}_i - \ddot{u}_i \frac{\Delta t}{2} \quad (81)$$

Since equation (73) is satisfied at both t_i and t_{i+1} , it may be written as

$$m \Delta \ddot{u}_i + C_i \Delta \dot{u}_i + k_i \Delta u_i = \Delta p_i \quad (82)$$

Combining equations (80), (81), and (82) yields the incremental equation of motion

$$K_i^* \Delta u_i = \Delta p_i^* \quad (83)$$

where

$$K_i^* = K_i - \left(\frac{3C_i}{\Delta t_i} \right) + \frac{6m}{\Delta t_i^2} \quad (84)$$

and

$$\Delta p_i^* = \Delta p_i + \left[\frac{6m}{\Delta t} + 3C_i \right] \dot{u}_i + \left[3m + \frac{C_i \Delta t}{2} \right] \ddot{u}_i \quad (85)$$

Once Δu_i is determined from equation (83), $\Delta \dot{u}_i$ is obtained from equation (81) and $\Delta \ddot{u}_i$ from equation (80). The updated values of u , \dot{u} , and \ddot{u} at step $(i+1)$ is computed from

$$\begin{aligned} u_{i+1} &= u_i + \Delta u_i \\ \dot{u}_{i+1} &= \dot{u}_i + \Delta \dot{u}_i \\ \ddot{u}_{i+1} &= \ddot{u}_i + \Delta \ddot{u}_i \end{aligned} \quad (86)$$

This step by step procedure described determines the response of the LACE spacecraft boom modeled as a nonlinear system. The numerical integration provides a time history of the response, namely deflection, u , velocity, v , and acceleration, a .

Since experimental data for a 23-foot LACE-model boom is available from AEC-ABLE Engineering, the length of the boom analyzed is taken to be 23 feet. In the parametric study, the parameters varied are the excitation amplitude, frequency and the coefficient of the cubic stiffness term. The excitation amplitudes used gives deflections of 2.5%, 5%, 10%, 20%, and 25% of the length of the spacecraft boom. The frequencies used

are $1/3\omega_n$ and $3\omega_n$. These frequencies are chosen based on the cubic term of the stiffness that generates subharmonic and superharmonic response at one-third and three times the excitation frequency, respectively. The coefficient of the cubic stiffness term is varied from 1.1 to 1.5 of the linear stiffness term.

The constant terms used in the equation of motion are as follows:

$$K = 3.02 \text{ lbs/in}$$

$$m = .1475 \text{ slugs}$$

$$c = .177 \text{ slugs/sec}$$

$$\omega_n = 4.6 \text{ rad/sec}$$

where $c = 2\sqrt{Km}\zeta$. The damping factor ζ was obtained from AEC-ABLE Engineering using the Logarithmic Decrement method. A 23 foot boom mounted in its deployment cannister rigidly attached to a wall yields $\zeta = .039$ and a 23-foot boom rigidly mounted to a wall yields $\zeta = .001$. The first case approximates the LACE spacecraft configuration. Both damping cases are considered in the present simulation.

D. CHAOTIC VIBRATION ANALYSIS

A comprehensive FORTRAN program called CHAOS was developed by Sarigul-Klijn [Ref. 22] to analyze chaotic vibrations. The time history data from the numerical simulation program is used by the CHAOS program for the chaotic vibration analysis. The program CHAOS currently has 12 analysis options. They are

1. Plot the time history
2. Plot onto toroidal phase space
3. Take Poincaré section of toroidal phase space
4. Plot onto 2-D phase space
5. Plot onto 2-D Van der Pol plane
6. Plot onto 3-D phase space
7. Take Poincaré section of 3-D phase space
8. 3-D Poincaré section of a 4-D hyperspace
9. Compute fourier power spectrum
10. Compute statistics
11. Compute Lyapunov exponent
12. Compute fractal correlation dimension

As discussed earlier, the stiffness term is modeled as a combination of linear and cubic terms. The coefficient of the cubic term is varied as a percentage of the linear term from 10% to 50%, and is seen to yield no significant changes in the response. Therefore, an average value of 30% is used in all subsequent numerical simulation.

In order to focus the present study within the scope of this research, the study is divided into four specific groups. Each group is identified by excitation frequency and damping. In each group, the excitation amplitudes are 20.8 lbs, 41.7 lbs, 83.4 lbs, 166.7 lbs, and 208.4 lbs respectively. This yields a deflection of 2.5%, 5%, 10%, 20%, and 25% of the length of the beam, respectively. Table VI contains the group identification.

Table VI GROUP IDENTIFICATION

GROUP	Ω	C
A	1.53	.77
B	13.8	.177
C	1.53	.0454
D	13.8	.0454

The initial analysis consists of studying four qualitative indicators of chaos. They are time history, fourier power spectrum, pseudo-phase plane and Poincare section respectively. Then, quantitative measures of the motion are computed.

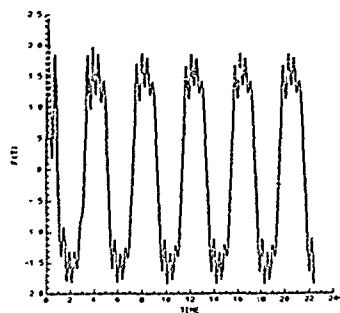
Figures 39-43 and 44-48 present the qualitative indicators for cases A and B respectively. The time history is initially transient and then becomes periodic in both cases. The fourier power spectrum indicates a broad-band frequency spectrum, with the number of spikes increasing with an increase in amplitude. The pseudo-phase plane plot indicates that the motion settles to a single limit cycle for case A and a double limit cycle for case B. The Poincaré section is very sparse and indicates a periodic system. The periodic time history also indicates a non-chaotic response.

Figures 49-53 and 54-58 present the qualitative indicators of chaos for groups C and D. In all cases, the time history is seen to be non-periodic and the Fourier power spectrum is observed to be broad-band. In both cases, there appears to be two limit cycles in the pseudo-phase plot. The Poincaré

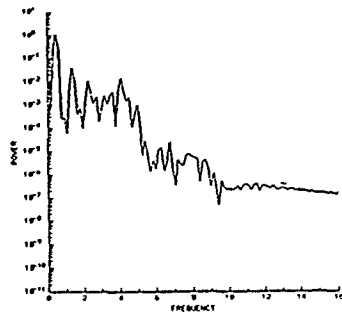
sections appear more dense than the previous groups and has the appearance of a strange attractor. These systems appear to be chaotic.

To ascertain the quantitative nature of the response, the fractal correlation dimension is computed for each group and is shown in Table VII. Figures 59 and 60 show the fractal dimension for increasing phase space dimension for two cases of damping with $F=20.8$ and $\Omega=1.53$ respectively. The plots for the other cases are given in Appendix J.

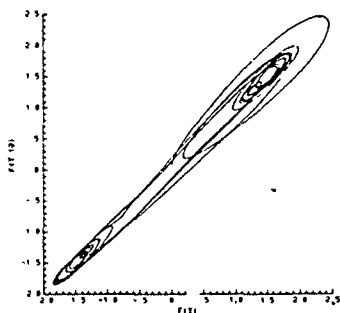
A non-integer fractal dimension is indicative of the presence of chaos in a system [Refs. 22,23,24,25]. This is consistent with the qualitative indicators of groups C and D. The inconsistency with groups A and B indicate that the fractal dimension by itself does not confirm the strangeness of the strange attractor as believed in the reported literature and must be used in conjunction with other indicators of chaos. Additional results pertaining to this parametric study are reported elsewhere [Ref. 26].



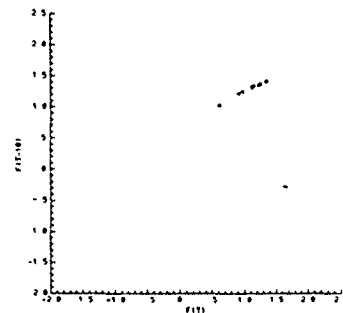
a. Time History



b. Fourier Power Spectrum

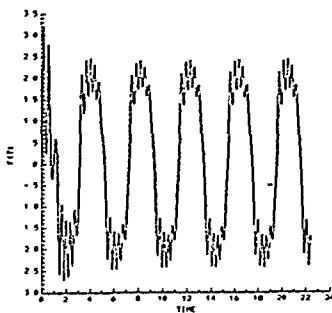


c. Pseudo Phase Plane

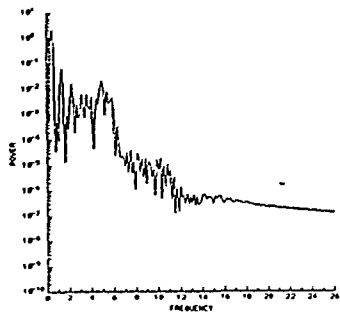


d. Poincaré Section

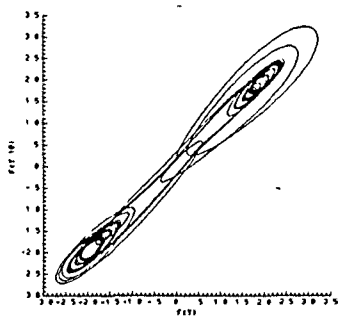
Figure 39. Qualitative Indicators Of Chaos.
 $F=20.8$ lbs, $\Omega=1.53$ Hz, $C=.177$.



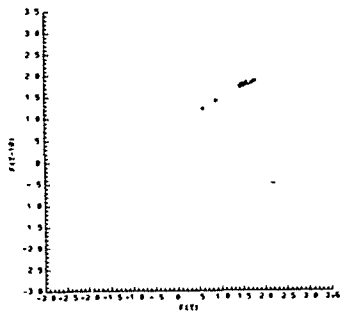
a. Time History



b. Fourier Power Spectrum

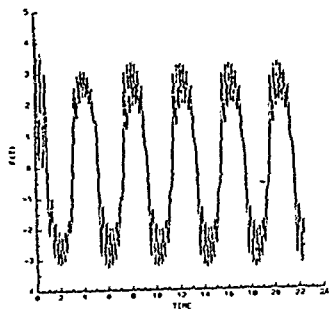


c. Pseudo Phase Plane

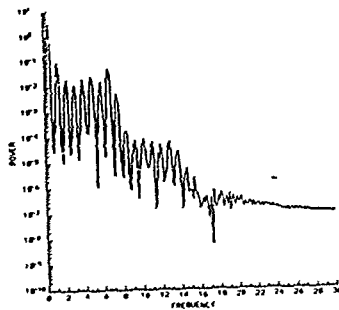


d. Poincaré Section

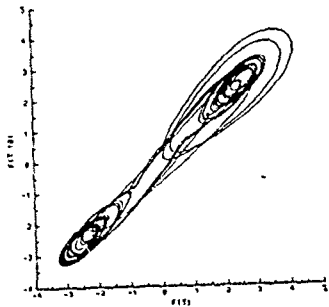
Figure 40. Qualitative Indicators Of Chaos.
 $F=41.68$ lbs, $\Omega=1.53$ Hz, $C=.177$



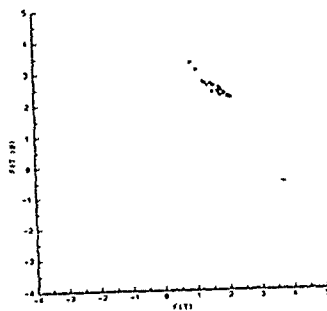
a. Time History



b. Fourier Power Spectrum

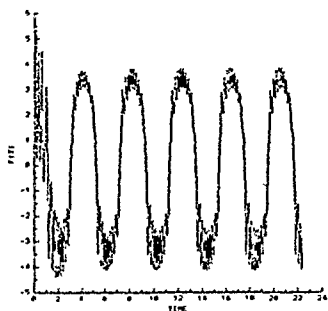


c. Pseudo Phase Plane

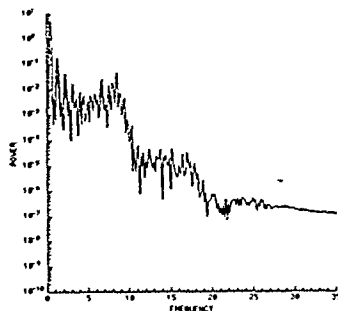


d. Poincaré Section

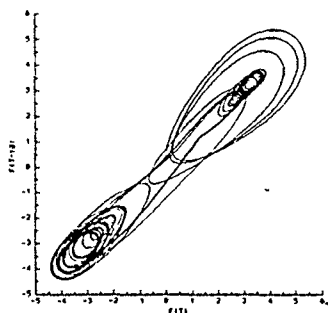
Figure 41. Qualitative Indicators Of Chaos.
 $F=83.352$ lbs, $\Omega=1.53$ Hz, $C=.177$



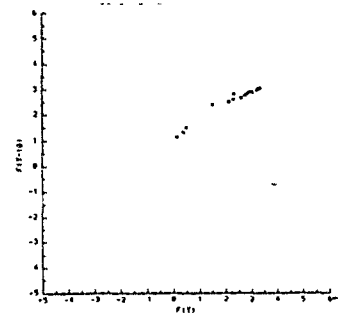
a. Time History



b. Fourier Power Spectrum



c. Pseudo Phase Plane



d. Poincaré Section

Figure 42. Qualitative Indicators Of Chaos.
 $F=166.7$ lbs, $\Omega=1.53$ Hz, $C=.177$

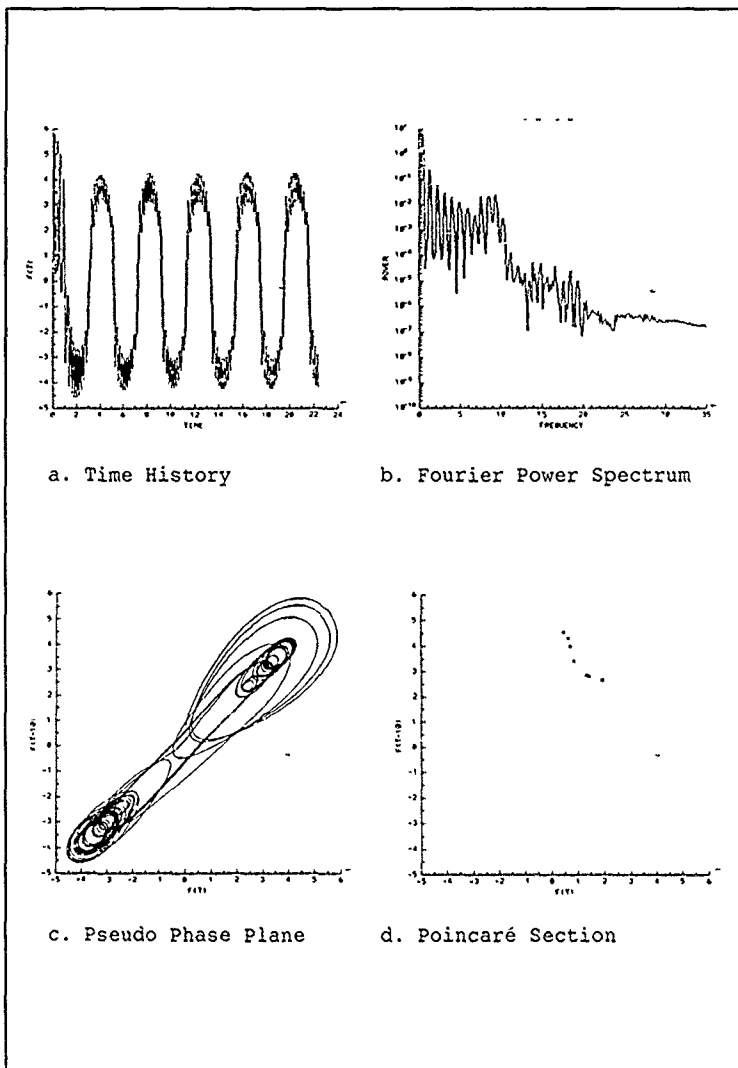
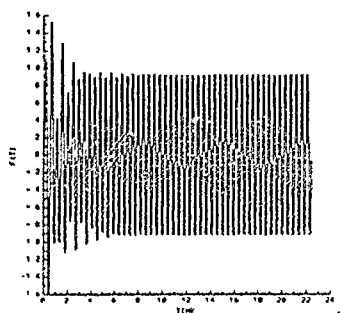
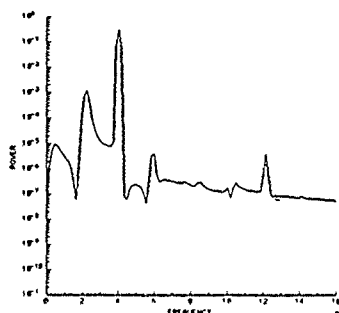


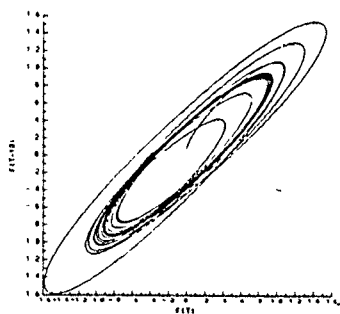
Figure 43. Qualitative Indicators Of Chaos.
 $F=208.38$ lbs, $\Omega=1.53$ Hz, $C=.177$



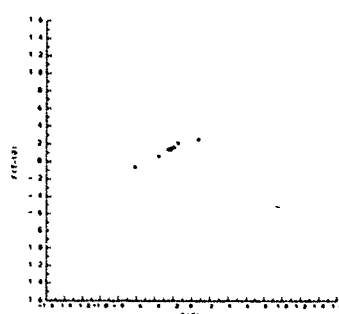
a. Time History



b. Fourier Power Spectrum

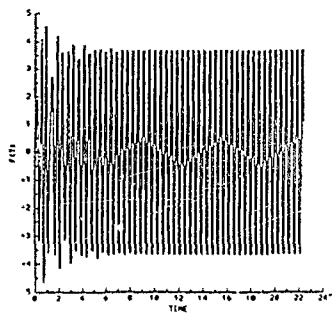


c. Pseudo Phase Plane

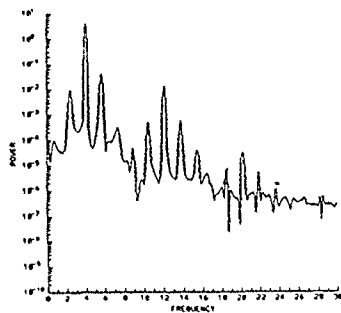


d. Poincaré Section

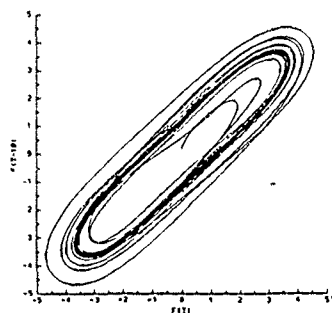
Figure 44. Qualitative Indicators Of Chaos.
 $F=20.8$ lbs, $\Omega=13.8$ Hz, $C=.177$



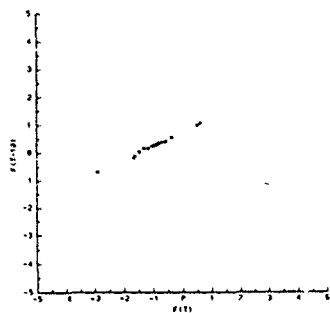
a. Time History



b. Fourier Power Spectrum

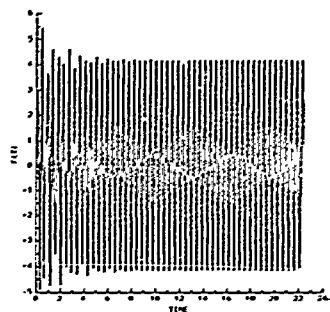


c. Pseudo Phase Plane

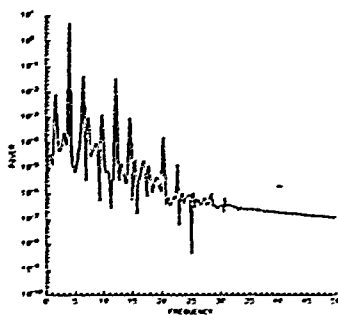


d. Poincaré Section

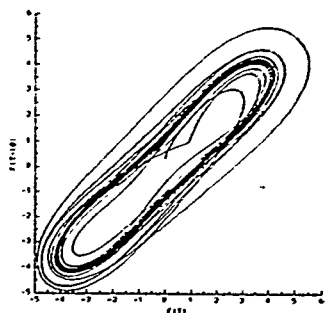
Figure 45. Qualitative Indicators Of Chaos.
 $F=41.68$ lbs, $\Omega=13.8$ Hz, $C=.177$



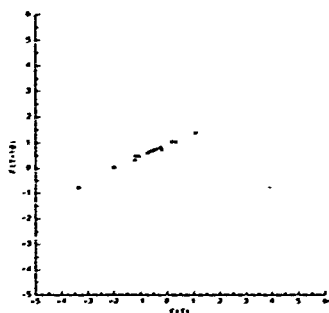
a. Time History



b. Fourier Power Spectrum



c. Pseudo Phase Plane



d. Poincaré Section

Figure 46. Qualitative Indicators Of Chaos.
 $F=83.352$ lbs, $Q=13.8$ Hz, $C=.177$

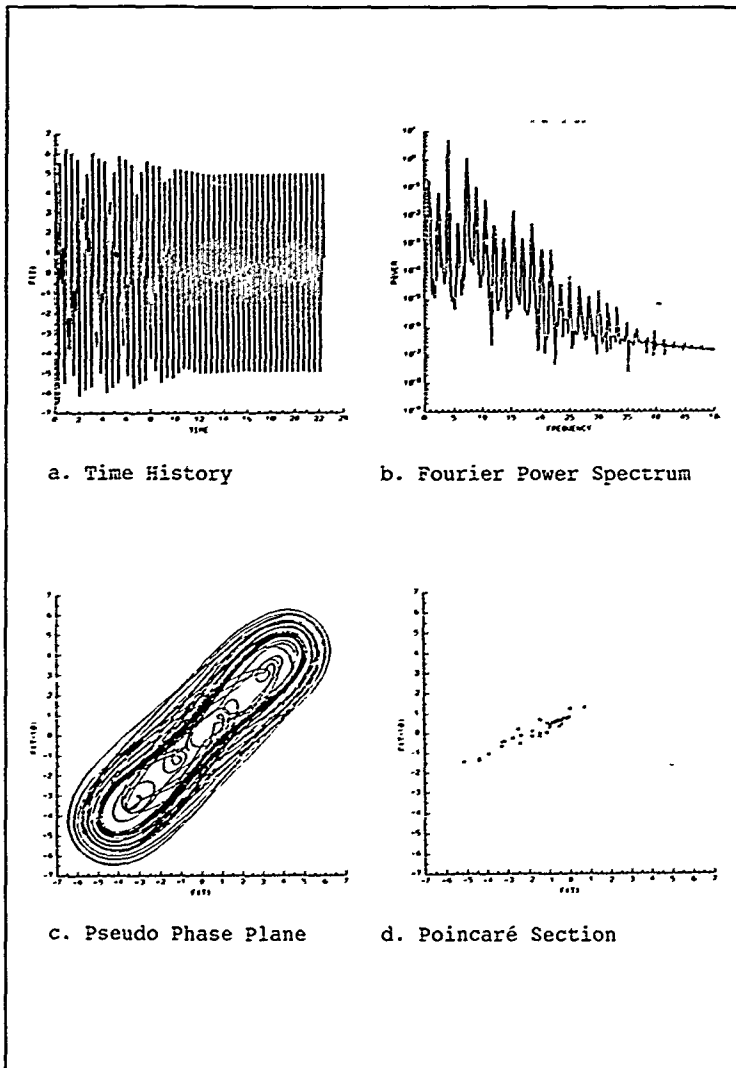
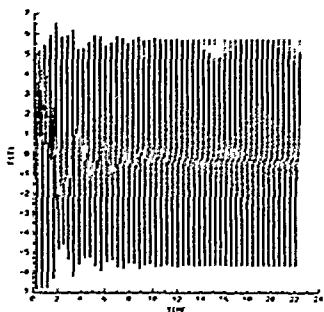
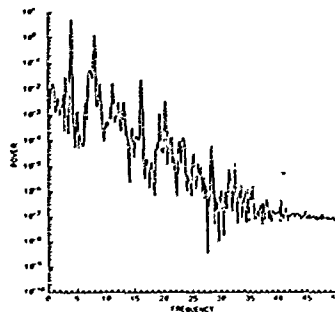


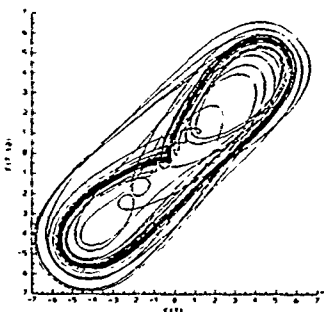
Figure 47. Qualitative Indicators Of Chaos.
 $F=166.7$ lbs, $\Omega=13.8$ Hz, $C=.177$



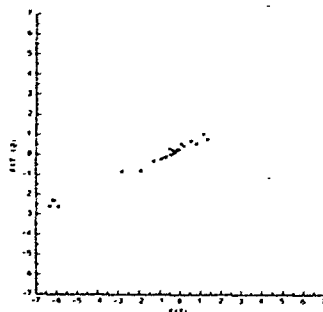
a. Time History



b. Fourier Power Spectrum



c. Pseudo Phase Plane



d. Poincaré Section

Figure 48. Qualitative Indicators Of Chaos.
 $F=208.38$ lbs, $\Omega=13.8$ Hz, $C=.177$

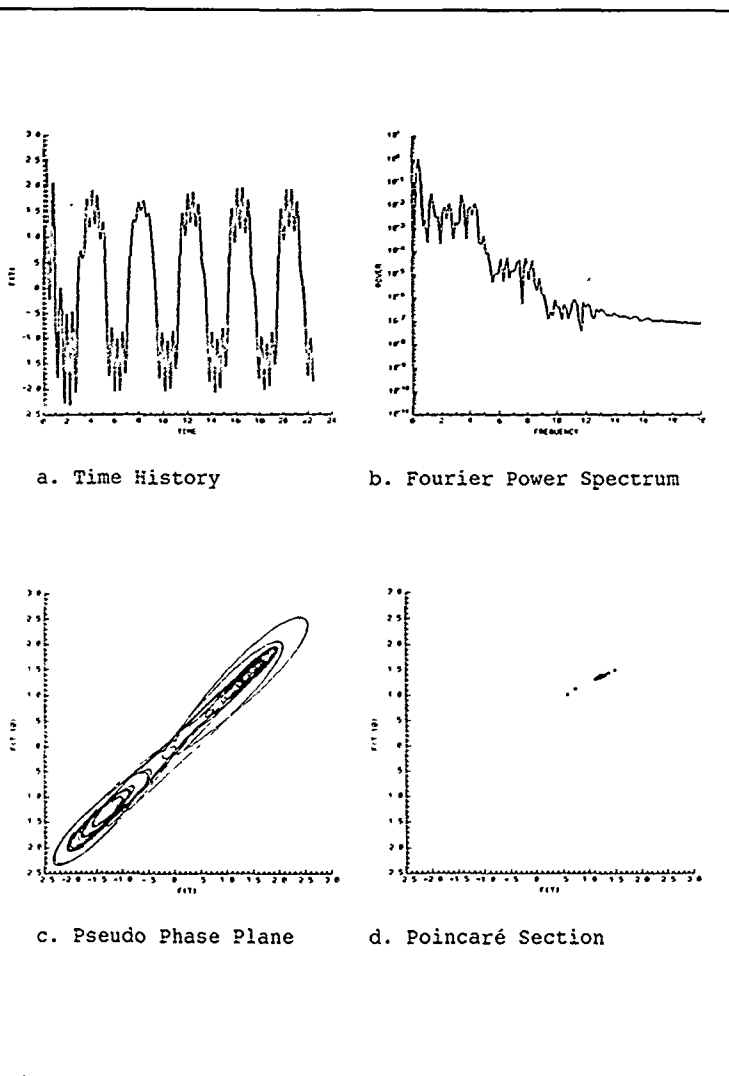
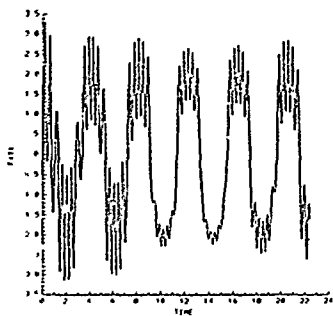
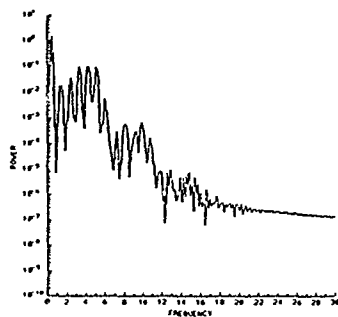


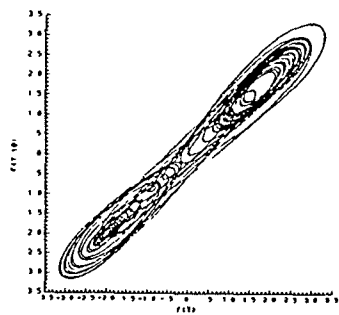
Figure 49. Qualitative Indicators Of Chaos.
 $F=20.8$ lbs, $\Omega=1.53$ Hz, $C=.0454$



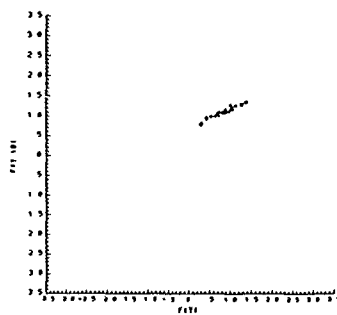
a. Time History



b. Fourier Power Spectrum

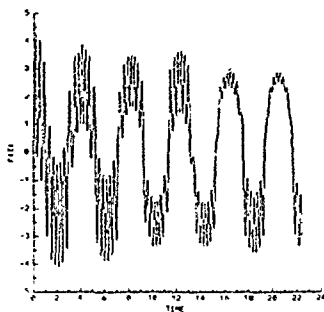


c. Pseudo Phase Plane

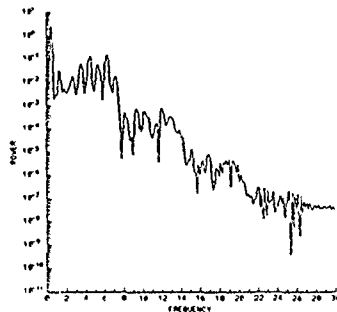


d. Poincaré Section

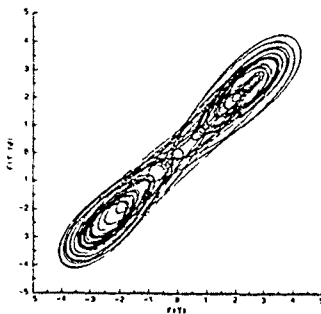
Figure 50. Qualitative Indicators Of Chaos.
 $F=41.68$ lbs, $\Omega=1.53$ Hz, $C=.0454$



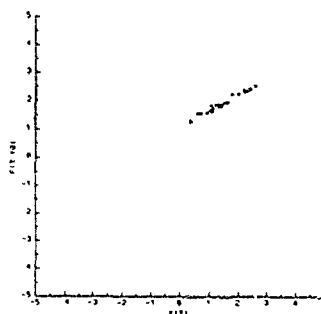
a. Time History



b. Fourier Power Spectrum

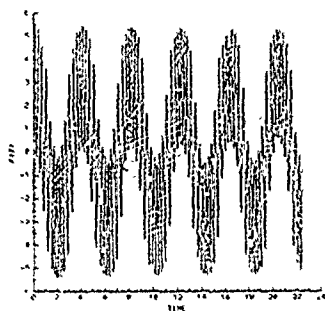


c. Pseudo Phase Plane

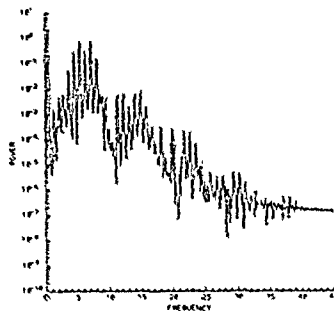


d. Poincaré Section

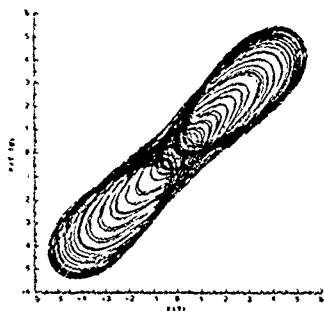
Figure 51. Qualitative Indicators Of Chaos.
 $F=83.352$ lbs, $\Omega=1.53$ Hz, $C=.0454$



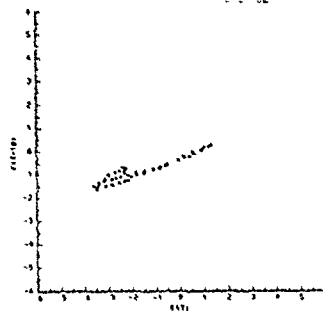
a. Time History



b. Fourier Power Spectrum

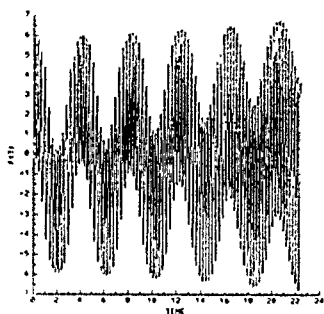


c. Pseudo Phase Plane

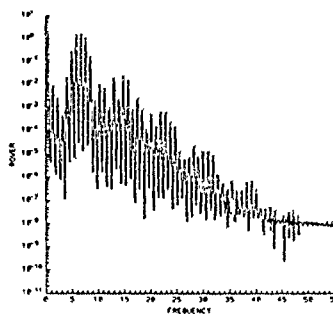


d. Poincaré Section

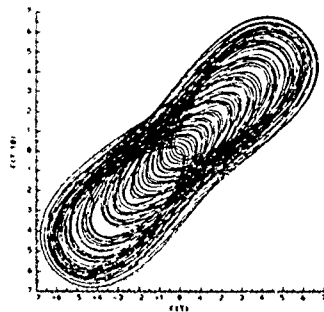
Figure 52. Qualitative Indicators Of Chaos.
 $F=166.7$ lbs, $\Omega=1.53$ Hz, $C=.0454$



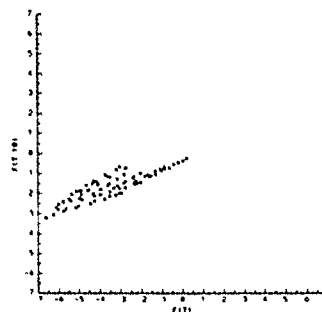
a. Time History



b. Fourier Power Spectrum

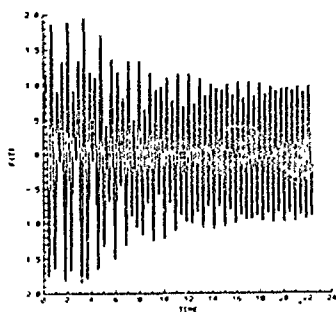


c. Pseudo Phase Plane

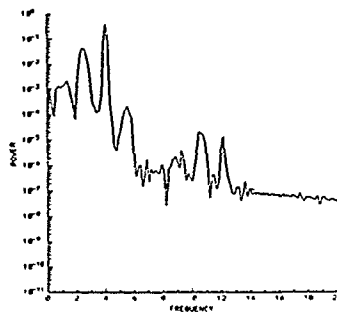


d. Poincaré Section

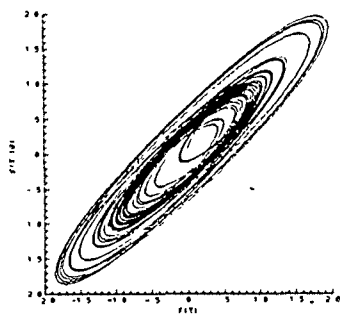
Figure 53. Qualitative Indicators Of Chaos.
 $F=208.38$ lbs, $\Omega=1.53$ Hz, $C=.0454$



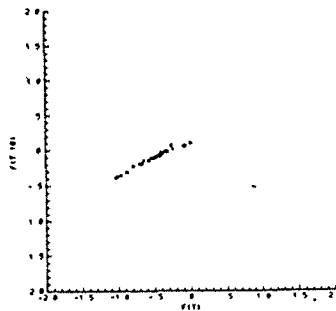
a. Time History



b. Fourier Power Spectrum

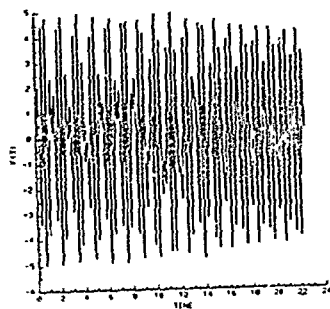


c. Pseudo Phase Plane

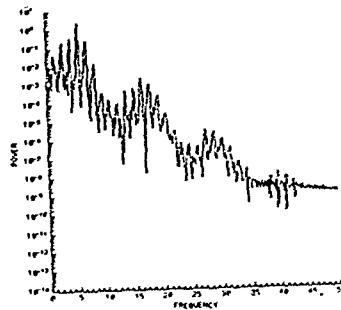


d. Poincaré Section

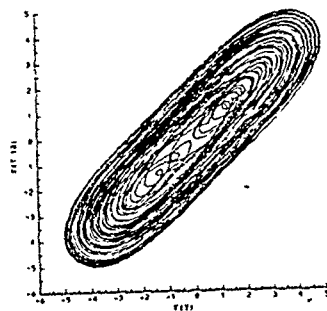
Figure 54. Qualitative Indicators Of Chaos.
 $F=20.8$ lbs, $\Omega=13.8$ Hz, $C=.0454$



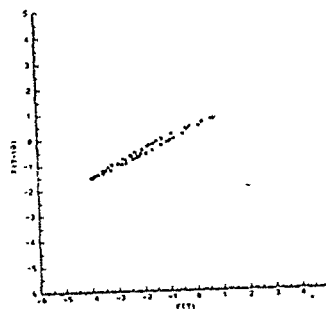
a. Time History



b. Fourier Power Spectrum

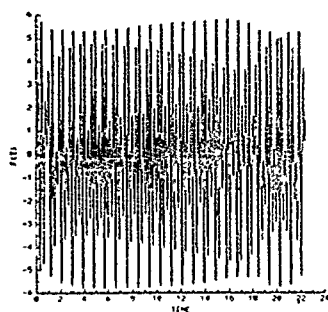


c. Pseudo Phase Plane

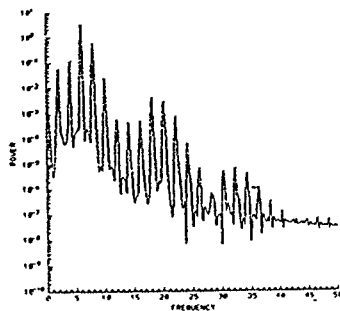


d. Poincaré Section

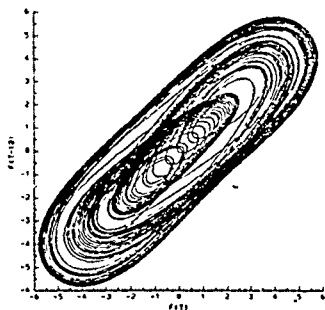
Figure 55. Qualitative Indicators Of Chaos.
 $F=41.68$ lbs, $\Omega=13.8$ Hz, $C=.0454$



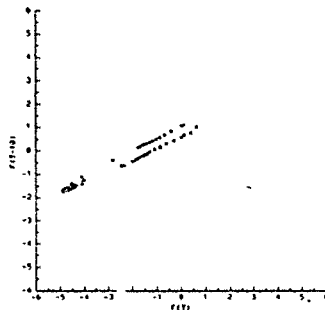
a. Time History



b. Fourier Power Spectrum

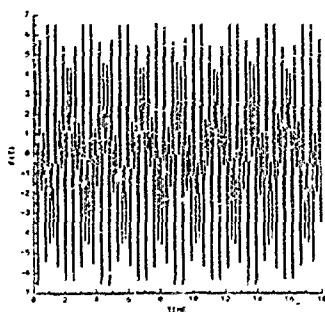


c. Pseudo Phase Plane

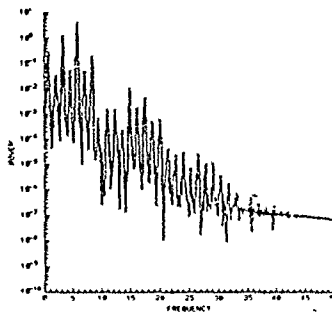


d. Poincaré Section

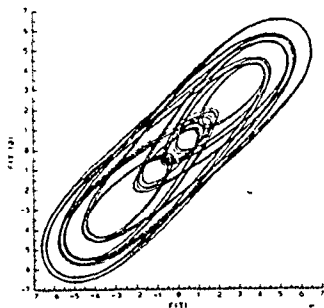
Figure 56. Qualitative Indicators Of Chaos.
 $F=83.352$ lbs, $\Omega=13.8$ Hz, $C=.0454$



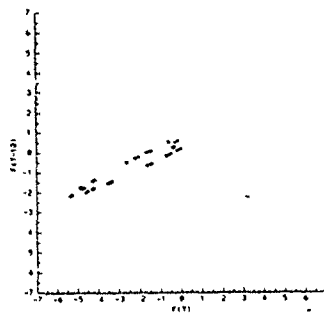
a. Time History



b. Fourier Power Spectrum

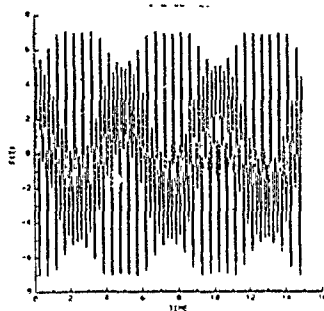


c. Pseudo Phase Plane

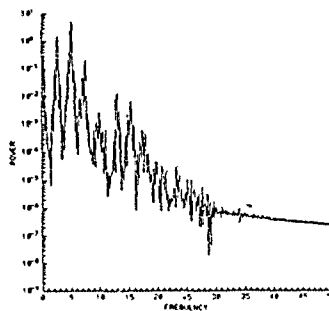


d. Poincaré Section

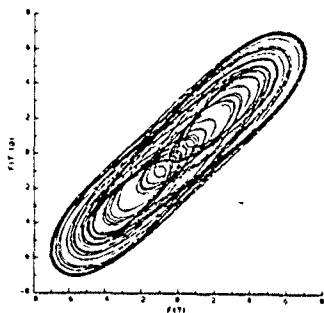
Figure 57. Qualitative Indicators Of Chaos.
 $F=166.7$ lbs, $\Omega=13.8$ Hz, $C=.0454$



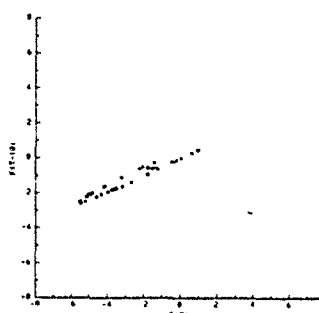
a. Time History



b. Fourier Power Spectrum



c. Pseudo Phase Plane



d. Poincaré Section

Figure 58. Qualitative Indicators Of Chaos.
 $F=208.38$ lbs, $\Omega=13.8$ Hz, $C=.0454$

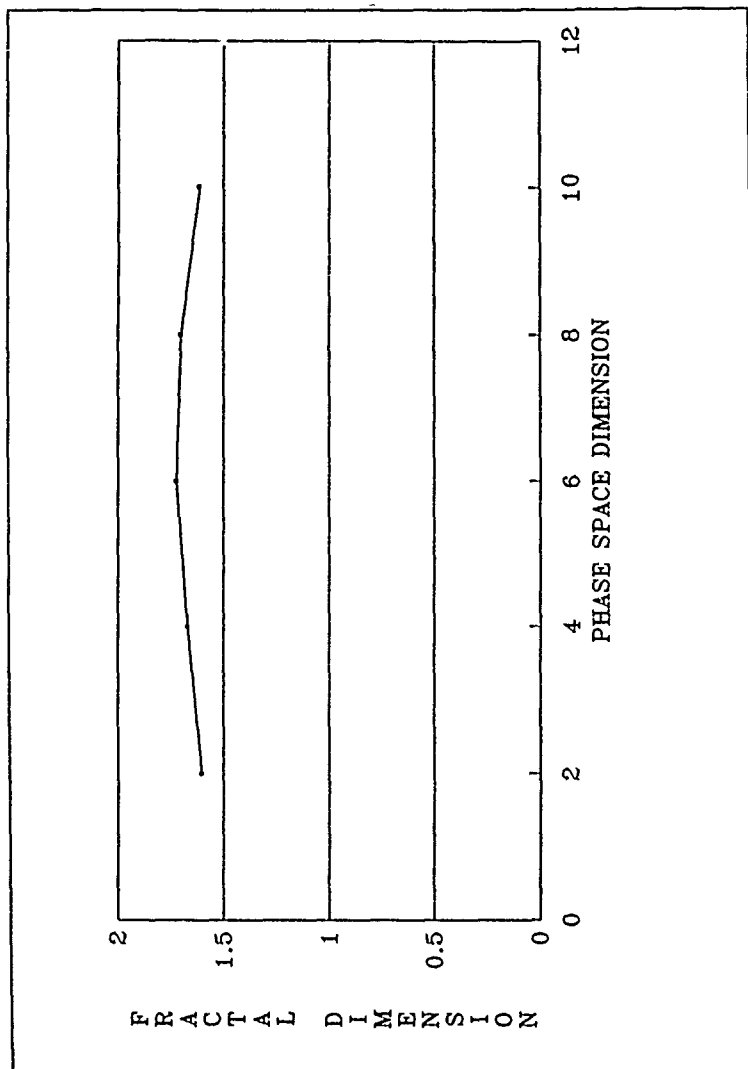


Figure 59. Fractal Dimension
 $F=20.8$, $\Omega=1.53$, $C=0.177$

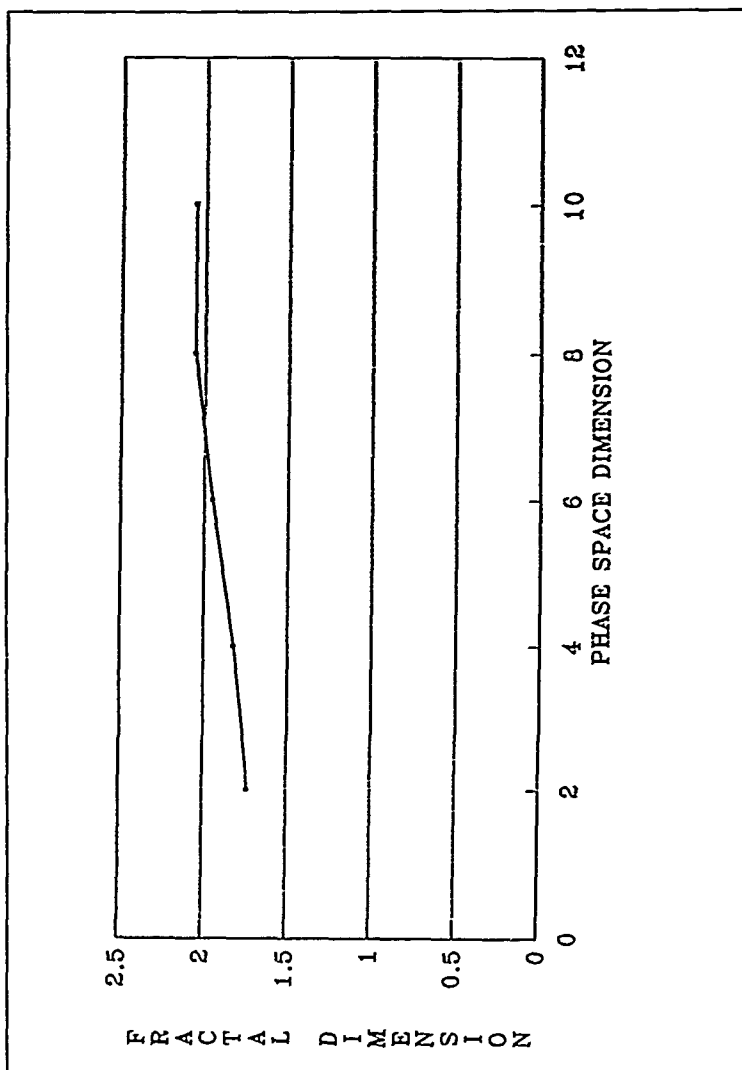


Figure 60. Fractal Dimension.
 $F=20.8$, $\Omega=1.53$, $C_u=0.0454$

Table VII. FRACTAL DIMENSION

	F	Q	C	FRACTAL DIMENSION
a)	20.8	1.53	.177	1.7
	41.7	1.53	.177	1.6
	83.4	1.53	.177	1.7
	166.7	1.53	.177	1.7
	208.4	1.53	.177	1.7
b)	20.8	13.8	.177	1.2
	41.7	13.8	.177	1.2
	83.4	13.8	.177	1.3
	166.7	13.8	.177	1.6
	208.4	13.8	.177	1.4
c)	20.8	1.53	.0454	2.05
	41.7	1.53	.0454	2.4
	83.4	1.53	.0454	2.05
	166.7	1.53	.0454	2.1
	201.4	1.53	.0454	2.6
d)	20.8	13.8	.0454	2.1
	41.7	13.8	.0454	2.4
	13.4	13.8	.0454	1.95
	166.7	13.8	.0454	2.1
	208.4	13.8	.0454	

VIII. CONCLUSIONS AND SCOPE FOR FURTHER RESEARCH

A. CONCLUSIONS

A detailed finite-element model of the LACE spacecraft has been developed using the finite element program GIFTS. A dynamic analysis was performed on the model to determine the natural frequencies and mode shapes. This model will provide a basis for comparison when actual orbital test data is available.

Thermoelastic effects of the LACE spacecraft boom were investigated for a worst case temperature scenario. The results indicated that the deflections induced would have negligible effect on the systems dynamics and would not affect the on-orbit systems identification or induced thermal flutter.

A preliminary study was conducted on a 23-foot section of the LACE spacecraft boom to investigate the possibility of chaotic vibrations occurring by varying the excitation amplitude and frequency. The system was modeled as a single-degree-of-freedom system with arbitrary nonlinear stiffness, and nonlinear damping excited by a sinusoidal function. A numerical integration program was developed to determine the system response using various excitation amplitudes and frequencies. Four qualitative methods, time history, fourier

power spectrum, pseudo-plane, and Poincaré section methods were used to evaluate chaotic vibrations. In addition, quantitative analysis included computation of correlation fractal dimension. It was evidenced that a combination of all approaches was needed to determine the nature of vibrations. Chaotic vibrations were present for the low-damped system while periodic response was indicated for highly damped systems.

A non-integer correlation fractal dimension, which is believed to be a quantitative indication of chaos in a system, was evidenced for both periodic and non-periodic responses of the system. This important result, which is further being confirmed from analysis of flight test data [Ref. 21] shows that the fractal dimension by itself is not enough to characterize the attractors found in nonlinear dynamical systems. Modeling the "looseness" of joints for triangular space trusses by Moon & Li [Ref. 27], who report interesting chaotic behavior, was brought to the attention of the author during the write-up of this report, which reveal the importance of understanding the nonlinear dynamic behavior of large flexible structures.

B. SCOPE FOR FUTURE RESEARCH

Future research may be beneficial in two main areas.

The first is the development of a multi-body dynamics model of the LACE spacecraft. A structural model using GIFTS has

already been developed. The results generated may be used to model the flexibility effects, while other effects introduced due to on-orbit, such as gravity gradients effects, atmospheric drag, etc., may be evaluated. These models may be used as baselines for comparison when the orbital test data from LACE becomes available. This comparison will provide an opportunity for improvements and adequacy of these computer models.

The availability of the orbital test data will provide information needed to conduct a more detailed study of chaotic vibrations on the fully deployed LACE spacecraft boom and assess the sensitivity of the highly flexible boom structure to accidental or intentional excitation. Assessing the exact nature of the response of large flexible space structures is important for missions that require accurate pointing accuracies and in suppression and control of vibrations.

APPENDIX A

\$! COM FILE TO GENERATE SIMPLE MODEL OF LACE SPACECRAFT AND
\$! DERIVE THE NATURAL FREQUENCIES.

\$! FILENAME IS LACE.COM

DEL LACE.*;*

\$ BEAMCS
LACE
OLB/LACECS
QUIT
\$ BULKM
LACE
OLB/LACEBM
QUIT
\$ LOADBC
LACE
OLB/LACEBC
QUIT
\$ BULKF
LACE
\$ OPTIM
LACE
1///
\$ ADSTIF
LACE
\$ ELSTFF
LACE
\$ STASS
LACE
\$ SUBS
LACE

\$ GENERATES SOLID CIRCULAR BEAM USING PROCESSOR BEAMCS

\$ FILENAME IS LACECS.SRC

CIRCS/1/.9585/

END

\$ SIMPLE FINITE ELEMENT MODEL OF THE LACE SPACECRAFT USING
BULKM


```
$  FILENAME IS LACEBM.SRC

$  ESTABLISH THE KEYPOINTS OF THE MODEL

KPOINT/1/0,0,0/2/0,1800,0/3/0,-900,0/
KPOINT/4/0,0,1800/5/50,0,0/

$  DEFINE MATERIAL PROPERTIES

ELMAT,4/1/3.E3,8.E6,.29,.000014752/

$  DEFINE BEAM CHARACTERISTICS

LETY
BEAM2
1,1

$  GENERATE THE BEAMS

SLINE,10/112/1,2,31/5/113/1,3,16/5/114/1,4,31/5/

END

$  GENERATES POINT MASSES FOR THE SPACECRAFT

$  FILENAME IS LACEBC.SRC

MASS/MASSP/1/6.4078E/2/.0906/3/.0906/4/.517/

END
```

APPENDIX B

The following calculations model structural honeycomb panels as aluminum panels with equivalent thickness and weight. The stiffness for a honeycomb panel is given as

$$D = \frac{E t h^2}{2(1-\nu)}$$

and the equation for an aluminum plate is

$$D = \frac{E t^3}{12(1-\nu^2)}$$

where

$$E = 9.9 \times 10^6 \text{ lbs/in}^2$$

$$\nu = .33$$

h = core thickness of honeycomb panel

t = face thickness

Throughout this appendix the following notation is used.

ρ = density

V = volume

W = weight

where subscripts h indicates honeycomb core and f refers to aluminum face skins. A panel size of 54" x 90" is assumed.

A. PRIMARY STRUCTURE

$$h = .9$$

$$t = .05$$

1. Determine Stiffness of Honeycomb Panel

$$D = \frac{(9.9 \times 10^6) (.05) (.9)^2}{2(1-.33)^2} = 2.25 \times 10^5 \text{ lbs./in}$$

2. Determine Equivalent Aluminum Plate Thickness

$$D = \frac{Et^3}{12(1-\nu^2)} \rightarrow 2.250 \times 10^5 = \frac{(9.9 \times 10^6) t^3}{2(1-.33^2)}$$

$$t = .624 \text{ in}$$

3. Determine Honeycomb Panel Mass

$$\rho_h^* = 6 \text{ lbs/ft}^3 = 3.47 \times 10^{-3} \text{ lbs/in}^3$$

$$\rho_f^* = 9.81 \times 10^{-2} \text{ lbs/in}^3$$

$$V_h = .9 \times 54 \times 96 = 4665.6 \text{ in}^3$$

$$V_f^* = .1 \times 54 \times 96 = 518.4 \text{ in}^3$$

$$W_h = 4665.6 \times 3.47 \times 10^{-3} = 16.2 \text{ lbs}$$

$$W_f^* = 518.4 \times 9.81 \times 10^{-2} = 50.8 \text{ lbs}$$

asterik items remain constant throughout the calculations

$$\text{Total weight} = 67 \text{ lbs}$$

$$\text{Total mass} = \frac{67 \text{ lbs}}{386.4 \text{ in/sec}^2} = .1734 \text{ (lbs-sec}^2\text{)/in (GIFTS units)}$$

4. Determine Equivalent Density

$$\text{Volume of aluminum panel} = .624 \times 54 \times 96 = 3234.8 \text{ in}^3$$

$$\text{Equivalent density} = \frac{.1735 \text{ (lbs-sec}^2\text{)/in}}{3234.8 \text{ in}^3} = 5.364 \times 10^{-5} \text{ (lbs-sec}^2\text{)/in}^4$$

B. SECONDARY STRUCTURE

1. Fixed and Deployable Solar Array Substrate

$$h = .4$$

$$t = .05$$

$$D = \frac{(9.9 \times 10^6) (.05) (.4)^2}{2(1-.33^2)} = 4.44 \times 10^4 \text{ lbs-in}$$

a. Determine Equivalent Aluminum Thickness

$$4.44 \times 10^4 \text{ lbs-in} = \frac{(9.9 \times 10^6) t^3}{12(1-.33^2)}$$

$$t = .3634 \text{ in}$$

b. Determine Honeycomb Panel Mass

$$V_h = .4 \times 54 \times 96 = 2073.6 \text{ in}^3$$

$$W_h = 2073.6 \times 3.47 \times 10^{-3} = 7.195 \text{ lbs}$$

$$\text{Total weight} = 58 \text{ lbs}$$

$$\text{Total mass} = 58/386.4 = .15 \text{ lbs-sec}^2/\text{in}$$

c. Determine Equivalent Density

$$\text{Volume of aluminum panel} = 1884 \text{ in}^3$$

$$\text{Equivalent density} = \frac{.15}{1884} = 7.96 \times 10^{-5} \text{ lbs-sec}^2/\text{in}^4$$

2. Deployable Sensor Panels

$$h = .65$$

$$t = .05$$

$$D = \frac{(9.9 \times 10^6) (.05) (.65)^2}{2(1-.33^2)} = 1.173 \times 10^5 \text{ lbs-in}$$

a. Determine Equivalent Aluminum Thickness

$$1.173 \times 10^5 = \frac{(9.9 \times 10^6) t^3}{12(1 - .33^2)}$$

$$t = .502 \text{ in}$$

b. Determine Honeycomb Mass

$$V_h = .65 \times 54 \times 96 = 3369.6 \text{ in}^3$$

$$W_h = 3369.6 \times 3.47 \times 10^3 = 11.7 \text{ lbs}$$

$$\text{Total weight} = 62.5 \text{ lbs}$$

$$\text{Total mass} = .1617 \text{ lbs-sec}^2/\text{in}$$

c. Determine Equivalent Density

$$\text{Volume of aluminum panel} = .502 \times 54 \times 96 = 2602.4 \text{ in}^3$$

$$\text{Equivalent density} = \frac{.1617}{2602.4} = 6.22 \times 10^{-5} \text{ (lbs-sec}^2\text{)/in}^3$$

APPENDIX C

\$! COM FILE TO GENERATE THE MAIN SPACECRAFT BODY

\$! FILENAME IS XLACE.COM

```
DEL LACE.*;*
$ BEAMCS
LACE
OLB/LACECS
QUIT
$ BULKM
LACE
OLB/LACEBM
QUIT
$ EDITM
LACE
OLB/LACEM
QUIT
$ LOADBC
LACE
MASS
OLB/MASS
QUIT
```

\$ GENERATES THE BEAM CROSS SECTIONS FOR THE LACE SPACECRAFT
\$ GENERATES THE FILE USING THE PROCESSOR BEAMCS
\$ SOURCE FILE NAME IS LACECS.SRC

ANGLE,11/1/2.875,3/.25,.25/0,1.938/90/

TBEAM,10/2/2.75,3/.25,.25/0,1.938/

CHANNEL/3/7.75,3/.125,.125/

CIRCH,1/9/5.605,5.5/0,5.5525/

END

\$ GENERATES LACE SPACECRAFT MAIN STRUCTURE

\$ GENERATES THE FILE USING THE PROCESSOR BULKM

\$ FILENAME IS LACEBM.SRC
 \$ ELEMENT MATERIAL DEFINITIONS
 \$ FRAME ELEMENTS
 ELMAT,4/1/1.8E4,9.9E6,.33,2.5382E-4/
 \$ PRIMARY STRUCTURE
 ELMAT,4/2/1.8E4,9.9E6,.33,5.364E-5/

 \$ SECONDARY STRUCTURE-FIXED AND DEPLOYABLE SOLAR ARRAY
 SUBSTRATE
 ELMAT,4/3/1.8E4,9.9E6,.33,8.1915E-5/
 \$ SECONDARY STRUCTURE-DEPLOYABLE SENSOR PANELS
 ELMAT,4/4/1.8E4,9.9E6,.33,6.22E-5/
 \$ SECONDARY STRUCTURE-DEPLOYABLE SENSOR ARMS AND BOTTOM PANEL
 ELMAT,4/5/1.8E4,9.9E6,.33,2.5382E-4/
 \$ DEFINE ELEMENT THICKNESS
 \$ PRIMARY STRUCTURE PANELS
 ETH,1/4/.624/
 \$ SECONDARY STRUCTURE PANELS- SOLAR ARRAY SUBSTRATE
 ETH,1/5/.3634/
 \$ SECONDARY STRUCTURE PANELS-DEPLOYABLE SENSOR PANELS
 ETH,1/6/.502/
 \$ SECONDARY STRUCTURE PANELS- DEPLOYABLE SENSOR ARMS AND
 BOTTOM
 \$ PANEL
 ETH,1/7/.125/
 \$ ESTABLISH THE KEYPOINTS FOR THE PRIMARY STRUCTURE
 KPOINT/1/26,26,0/2/-26,26,0/3/26,-26,0/4/-26,-26,0/
 KPOINT/5/26,26,41.75/6/-26,26,41.75/7/26,-26,41.75/8/-26,-26
 ,41.75/

KPOINT/9/26,26,68.375/10/-26,26,68.375/11/26,-26,68.375/
KPOINT/ 12/-26,-26,68.375/13/26,26,96/
KPOINT/14/-26,26,96/15/26,-26,96/16/-26,-26,96/

\$ ESTABLISH KEYPOINTS FOR THE CIRCULAR ARCS

\$ SIDE C+Y

KPOINT/17/13,26,68.375/18/13,26,76.5/19/13,26,87.5/20/13,26,
96/
KPOINT/21/18.5,26,82/22/7.5,26,82/

\$ SIDE C-Y

KPOINT/23/-13,-26,68.375/24/-13,-26,76.5/25/-13,-26,87.5/
KPOINT/26/-13,-26,96/27/-7.5,-26,82/28/-18.5,-26,82/

\$ SIDE +Z

KPOINT/29/26,0,96/30/5.5,0,96/31/-5.5,0,96/32/-26,0,96/
KPOINT/33/0,-5.5,96/34/0,5.5,96/

\$ GENERATE VERTICAL ANGLE BEAM MEMBERS FOR C-SECTION PANELS

LETY/BEAM2/1,1/

SLINE,10/L913/9,13,6/10/L1014/10,14,6/9/L1216/12,16,6/10/
SLINE,10/L1115/11,15,6/9/

\$ GENERATE VERTICAL ANGLE BEAM MEMBERS FOR B-SECTION PANELS

SLINE,10/L59/5,9,3/6/L610/6,10,3/5/L812/8,12,3/7/L711/7,11,3
/5/

\$ GENERATE VERTICAL ANGLE BEAM MEMBERS FOR A-SECTION PANELS

SLINE,10/L15/1,5,3/2/L26/2,6,3/1/L48/4,8,3/3/L37/3,7,3/1/

\$ GENERATE HORIZONTAL ANGLE BEAMS FOR TOP AND BOTTOM MEMBERS

\$ BOTTOM MEMBERS

SLINE/L12/1,2,6/L34/3,4,6/L13/1,3,5/L24/2,4,5/

\$ TOP MEMBERS

SLINE/L1320/13,20,2/L1420/14,20,5/L1432/14,32,3/L1632/16,32,3/
SLINE/L1626/16,26,2/L1526/15,26,5/L1329/13,29,3/L1529/15,29,3/

\$ GENERATE HORIZONTAL T-SECTION BEAM MEMBERS

\$ B-SECTION PANELS

LETY/BEAM2/1,2/
SLINE,10/L56/5,6,6/7/L78/7,8,6/5/L57/5,7,5/6/L68/6,8,5/5/

\$ C-SECTION PANELS

SLINE,10/L917/9,17,2/13/L1017/10,17,5/14/L1012/10,12,5/9/
SLINE,10/L1223/12,23,2/10/L1123/11,23,5/9/L911/9,11,5/10/

\$ GENERATE LINES ASSOCIATED WITH CIRCULAR ARCS

SLINE/L1718/17,18,2/L1920/19,20,2/L2324/23,24,2/L2526/25,26,2/
SLINE/L2930/29,30,2/L3132/31,32,2/

\$ GENERATE CIRCULAR ARCS

\$ C-Y SIDE PANEL

CARC/C1819/18,22,19,4/C1918/19,21,18,4/

\$ C-Y SIDE PANEL

CARC/C1819/18,22,19,4/C1918/19,21,18,4/

\$ C-Y SIDE PANEL

CARC/C2425/24,28,25,4/C2524/25,27,24,4/

\$ TOP PANEL +Z

CARC/C3031/30,33,31,4/C3130/31,34,30,4/

\$ GENERATE COMPLINES

COMPLINE/L1314/L1320,L1420/L1416/L1432,L1632/I-1315/L1329,L15
29/
COMPLINE/L1516/L1526,L1626/L1720/L1718,C1819,L1920/
COMPLINE/L2017/L1920,C1918,L1718/L2326/L2324,C2425,L2526/
COMPLINE/L2326/L2324,C2425,L2526/L2623/L2526,C2524,L2324/
COMPLINE/L910/L917,L1017/L1112/L1123,L1223/
COMPLINE/L2932/L2930,C3031,L3132/L3229/L3132,C3130,L2930/

\$ GENERATE GRID ELEMENTS

GETY/QB4/2,4/

\$ A-PANELS

GRID4/A+Y/L12,L56,L15,L26/A-X/L24,L68,L26,L48/
GRID4/A-Y/L34,L78,L48,L37/A+X/L13,L57,L15,L37/

\$ B-PANELS

GRID4/B+Y/L56,L910,L59,L610/B-X/L68,L1012,L610,L812/
GRID4/B-Y/L78,L1112,L812,L711/B+X/L57,L911,L59,L711/

\$ GENERATE C-PANELS

GRID4/C+YL/L917,L2017,L1320,L913/C+YR/L1017,L1014,L1426,L1720/
GRID4/C-YL/L1223,L2325,L1626,L1216/C-YR/L1123,L1115,L1526,L2
623/
GRID4/C+X/L913,L1315,L1115,L911/C-X/L1014,L1416,L1216,L1012/

\$ GENERATE TOP PANEL

GRID4/ZL/L1529,L1516,L1632,L2932/ZR/L1329,L3229,L1432,L1314/

\$ GENERATE RF PANEL

GRID4/RF/L56,L68,L78,L57/

\$ GENERATE BOTTOM PANEL

GETY/QB4/5,7/
GRID4/BOTTOM/L12,L24,L34,L13/

\$ GENERATE KEYPOINTS FOR SENSOR PANELS AND SENSOR ARMS

KPOINT/35/19,26,0/36/19,75.25,0/37/-19,26,0/38/-19,75.25,0/
KPOINT/39/-26,19,0/40/-75.25,19,0/41/-26,-19,0/42/-75.25,-19
,0/
KPOINT/43/-19,-26,0/44/-19,-75.25,0/45/19,-26,0/46/19,-75.25
,0/
KPOINT/47/26,-19,0/48/75.25,-19,0/49/26,19,0/50/75.25,19,0/
KPOINT/51/79.03,79.03,0/52/-79.03,79.03,0/53/-79.03,-79.03,0/
KPOINT/54/79.03,-79.03,0/

\$ GENERATE LINES FOR SENSOR PANELS

SLINE/L3536/35,36,5/L3738/37,38,5/L3537/35,37,4/L3638/36,38,4/
SLINE/L4344/43,44,5/L4546/45,46,5/L4345/43,45,4/L4446/44,46,4/
SLINE/L4748/47,48,5/L4950/49,50,5/L4749/47,49,4/L4850/48,50,4/

\$ GENERATE GRID ELEMENTS

GETY/QB4/4,6/

GRID4/+Y/L3536,L3738,L3537,L3638/-X/L3940,L4142,L3941,L4042/
GRID4/-Y/L4344,L4546,L4345,L4446/+X/L4748,L4950,L4749,L4850/

\$ GENERATE CHANNEL BEAM ELEMENTS FOR SENSOR ARMS

LETY/BEAM2/3,1/
SLINE2,10/L151/1,51,6/52/L252/2,52,6/51/L453/4,53,6/54/
SLINE,10/L354/3,54,6/53/

\$ GENERATE KEYPOINTS FOR SOLAR PANEL FOLDOUTS

KPOINT/55/24,26,96/56/24,68.5,96/57/-24,26,96/58/-24,68.5,96/
KPOINT/59/-26,24,96/60/-68.5,24,96/61/-26,-24,96/62/-68.5,-2
4,96/
KPOINT/63/-24,-26,96/64/-24,-68.5,96/65/24,-26,96/66/24,-68.
5,96/
KPOINT/67/26,-24,96/68/68.5,-24,96/69/26,24,96/70/68.5,24,96/

\$ GENERATE LINES FOR SOLAR PANEL FOLDOUTS

SLINE/L5556/55,56,3/L5758/57,58,3/L5557/55,57,3/L5658/56,58,3/
SLINE/L5960/59,60,3/L6162/61,62,3/L5961/59,61,3/L6062/60,62,3/
SLINE/L6364/63,64,3/L6566/65,66,3/L6365/63,65,3/L6466/64,66,3/
SLINE/L6768/67,68,3/L6970/69,70,3/L6769/67,69,3/L6870/68,70,3/

\$ GENERATE GRID ELEMENTS

GETY/QB4/3,5/

GRID4/D+Y/L5556,L5758,L5557,L5658/D-X/L5960,L6162,L5961,L6062/
GRID4/D-Y/L6364,L6566,L6365,L6466/D+X/L6768,L6970,L6769,L6870/

\$ GENERATE KEYPOINTS FOR SOLAR FIXED PANELS

\$ A+Y PANELS

KPOINT/71/-26,26,20/72/-26,26,46/73/-14,26,46/74/-14,26,60/
KPOINT/75/14,26,60/76/14,26,46/77/26,26,46/78/26,26,20/

\$ A-Y

KPOINT/79/26,-26,20/80/26,-26,46/81/14,-26,46/82/14,-26,60/
KPOINT/83/-14,-26,60/84/-14,-26,46/85/-26,-26,46/86/-26,-26,
20/

\$ C+X

KPOINT/87/26,26,30/88/26,26,45/89/26,14,45/90/26,14,56.01/
KPOINT/91/26,26,56.01/92/26,26,88.5/93/26,-26,88.5/94/26,-26,
56.01/
KPOINT/95/26,-14,56.01/96/26,-14,45/97/26,-26,45/98/26,-26,30/

\$ C-X

KPOINT/99/-26,26,30/100/-26,26,45/101/-26,14,45/102/-26,14,5
6.01/

KPOINT/103/-26,26,56.01/104/-26,26,88.5/105/-26,-26,88.5/
KPOINT/106/-26,-26,56.01/107/-26,-14,56.01/108/-26,-14,45/
KPOINT/109/-26,-26,45/110/-26,-26,30/

END

\$ EDIT THE MODEL-GENERATE VERTICAL ANGLE BEAM ELEMENTS

\$ GENERATES THE FILE USING THE PROCESSOR EDITM

\$ FILE NAME IS LACEM.SRC

PTRM/1/PTRTH/1

\$ GENERATE TOP ANGLE MEMBERS

BEAM2/13,55,29/20,55,29/20,57,32/14,57,32/
BEAM2/14,59,20/32,59,31/32,61,31/16,61,26/
BEAM2/16,63,32/26,63,32/26,65,32/15,65,29/
BEAM2/15,67,26/29,67,26/29,69,30/13,69,20/

\$ GENERATE BOTTOM ANGLE MEMBERS

BEAM2/1,35,3/35,37,3/2,37,4/
BEAM2/2,39,1/39,41,1/4,41,3/
BEAM2/4,43,2/43,45,2/3,45,1/
BEAM2/3,47,4/47,49,4/1,49,2/
BEAM2/419,422,1/411,414,1/135,139,1/138,142,1/

\$ GENERATE HOLLOW CIRCULAR BEAM CROSS SECTION FOR CYLINDRICAL
\$ CANNISTERS

PTRTH/9/

BEAM2/19,364,9/25,352,9/31,405,9/

END

\$ GENERATES POINT AND GRID MASSES FOR THE LACE SPACECRAFT

\$ GENERATES THE FILE USING THE PROCESSOR LOADBC

\$ SOURCE FILE NAME IS MASS.SRC

\$ GENERATE MASS DISTRIBUTIONS FOR A-PANELS

\$ MASS LOADING FOR A-Y PANEL

MASSP/8/6.31E-3/166/1.54E-2/165/1.65E-2/
MASSP/164/1.65E-2/163/1.19E-2/7/2.87E-3/
MASSP/133/9.76E-3/325/2.48E-2/324/2.25E-2/
MASSP/323/2.25E-2/322/1.65E-2/134/7.4E-3/
MASSP/4/6.31E-3/142/1.23E-2/141/8.88E-3/
MASSP/140/8.88E-3/139/7.4E-3/3/7.4E-3/

\$ MASS LOADING FOR A+Y PANEL

MASSP/5/2.87E-3/159/1.37E-2/160/2.03E-2/
MASSP/161/1.61E-2/162/9.47E-3/6/2.87E-3/
MASSP/131/5.27E-3/315/1.61E-2/316/2.69E-2/
MASSP/317/2.93E-2/318/1.61E-2/132/2.87E-3/
MASSP/1/5.27E-3/135/5.27E-3/136/9.47E-3/
MASSP/137/1.61E-2/138/9.47E-3/2/2.87E-3/

\$ MASS LOADING FOR A-X PANEL

MASSP/6/7.01E-3/170/1.86E-2/171/3.07E-2/
MASSP/172/2.36E-2/8/7.97E-3/
MASSP/132/2.55E-2/319/5.57E-2/320/7.22E-2/
MASSP/321/4.66E-2/133/7.97E-3/
MASSP/2/2.2E-2/146/4.05E-2/147/4.48E-2/
MASSP/148/2.64E-2/4/3.44E-3/

\$ MASS LOADING FOR A+X PANEL

MASSP/7/3.44E-3/169/1.88E-2/168/2.3E-2/
MASSP/167/7.66E-3/5/3.44E-3/
MASSP/134/1.32E-2/328/4.7E-2/
MASSP/327/6.0E-2/326/3.89E-2/131/1.62E-2/
MASSP/3/1.32E-2/145/3.16E-2/144/4.03E-2/
MASSP/143/3.46E-2/1/1.62E-2/

\$ GENERATES MASS DISTRIBUTIONS FOR B-PANELS

\$ MASS LOADING FOR B+Y PANEL

MASSP/5/8.4E-3/127/8.4E-3/329/8.4E-3/159/8.4E-3/
MASSP/160/1.92E-3/330/1.92E-3/161/3.4E-2/
MASSP/331/3.4E-2/162/1.59E-2/332/1.59E-2/

\$ MASS LOADING FOR B-X PANEL

MASSP/170/7.47E-3/171/7.47E-3/172/7.47E-3/
MASSP/333/7.47E-3/335/7.47E-3/
MASSP/334/8.9E-3/177/2.16E-3/

\$ MASS LOADING FOR B+X PANEL

MASSP/11/4.27E-3/184/8.83E-3/183/9.81E-3/
MASSP/182/1.7E-2/9/1.24E-2/130/4.27E-3/
MASSP/342/1.34E-2/341/1.89E-2/340/3.48E-2/
MASSP/127/2.57E-2/7/6.91E-4/169/5.25E-3/
MASSP/168/9.81E-3/167/1.79E-2/5/1.39E-2/

\$ GENERATES MASS DISTRIBUTIONS FOR C-PANELS

\$ MASS LOADING FOR C+Y PANEL

MASSP/344/3.96E-3/345/3.96E-3/347/3.96E-3/
MASSP/348/3.96E-3/174/3.96E-3/175/3.96E-3/

\$ MASS LOADING FOR C-Y PANEL

MASSP/181/4.84E-3/357/4.84E-3/360/9.68E-3/
MASSP/363/4.84E-3/366/4.84E-3/
MASSP/180/4.84E-3/356/4.84E-3/359/9.68E-3/
MASSP/362/4.84E-3/365/4.84E-3/

\$ MASS LOADING FOR C-X PANEL

MASSP/379/8.67E-3/380/8.67E-3/383/8.67E-3/
MASSP/384/8.67E-3/387/8.67E-3/388/8.67E-3/

\$ MASS LOADING FOR C+X PANEL

MASSP/158/3.35E-3/378/3.35E-3/368/3.08E-3/
MASSP/369/3.08E-3/372/3.08E-3/373/3.08E-3/
MASSP/371/3.81E-3/

\$ GENERATES MASS DISTRIBUTIONS FOR THE TOP PANEL

MASSP/16/5.29E-3/153/4.21E-3/32/3.56E-3/
MASSP/152/9.7E-4/14/2.06E-3/15/2.06E-3/
MASSP/158/9.7E-4/29/9.7E-4/157/9.7E-4/
MASSP/13/2.06E-3/26/5.71E-3/156/3.77E-3/
MASSP/155/3.77E-3/154/2.47E-3/149/2.47E-3/
MASSP/150/3.44E-3/151/3.44E-3/20/2.47E-3/
MASSP/394/4.21E-3/393/2.26E-3/392/2.26E-3/
MASSP/391/9.7E-4/30/9.7E-4/193/9.7E-4/
MASSP/194/9.7E-4/31/9.7E-4/195/9.7E-4/
MASSP/196/9.7E-4/398/9.7E-4/397/1.94E-3/
MASSP/396/1.94E-3/395/9.7E-4/

\$ GENERATE MASS DISTRIBUTIONS FOR THE RF PANEL

MASSP/8/2.16E-3/172/2.16E-3/171/2.52E-3/
MASSP/170/2.16E-3/6/2.16E-3/166/5.49E-3/
MASSP/410/1.29E-2/406/8.34E-3/402/2.16E-3/

MASSP/162/2.16E-3/165/6.0E-3/409/1.18E-2/
 MASSP/405/1.66E-2/401/1.07E-2/161/1.07E-2/
 MASSP/164/6.0E-3/408/9.88E-3/404/2.32E-2/
 MASSP/400/1.93E-2/160/1.93E-2/163/5.49E-3/
 MASSP/407/9.37E-3/403/1.46E-2/399/1.07E-2/
 MASSP/159/1.07E-2/7/2.56E-3/169/6.03E-3/
 MASSP/168/6.32E-3/167/2.16E-3/5/2.16E-3/

\$ GENERATES MASS DISTRIBUTION ON THE BOTTOM PANEL

MASSP/4/5.85E-3/148/9.65E-3/147/1.06E-2/
 MASSP/146/8.36E-3/2/5.85E-3/142/3.19E-2/
 MASSP/422/3.77E-2/418/1.73E-2/414/2.23E-2/
 MASSP/138/1.28E-2/141/2.83E-2/421/5.5E-2/
 MASSP/417/6.07E-2/413/4.34E-2/137/1.15E-2/
 MASSP/140/2.57E-2/420/5.8E-2/416/6.21E-2/
 MASSP/412/3.39E-2/136/5.91E-3/139/2.94E-2/
 MASSP/419/3.78E-2/415/1.9E-2/411/1.56E-2/
 MASSP/135/7.14E-3/3/5.85E-3/145/7.14E-3/
 MASSP/144/8.62E-3/143/1.1E-2/1/5.85E-3/

\$ GENERATES MASS DISTRIBUTIONS ON THE SENSOR PANELS AND SENSOR ARMS

\$ GENERATE MASS LOADINGS FOR THE SENSOR ARMS

MASSP/1/8.16E-3/283/7.89E-3/284/1.12E-2/
 MASSP/285/7.89E-3/286/8.16E-3/51/7.89E-3/
 MASSP/2/8.16E-3/287/7.89E-3/288/1.12E-2/
 MASSP/289/7.89E-3/290/8.16E-3/52/7.89E-3/
 MASSP/3/8.16E-3/295/7.89E-3/296/1.12E-2/
 MASSP/297/7.89E-3/298/8.16E-3/54/7.89E-3/
 MASSP/4/8.16E-3/291/7.89E-3/292/1.12E-2/
 MASSP/293/7.89E-3/294/8.16E-3/53/7.89E-3/

\$ GENERATE MASS LOADINGS FOR THE SENSOR PANELS

\$ GENERATE MASS LOADINGS FOR +Y PANEL

MASSP/37/7.83E-3/246/6.47E-3/247/5.56E-3/
 MASSP/248/5.63E-3/38/6.02E-3/
 MASSP/250/4.66E-3/426/1.22E-2/
 MASSP/427/1.22E-2/428/7.18E-3/252/4.66E-3/
 MASSP/249/4.66E-3/423/1.22E-2/424/1.22E-2/
 MASSP/425/7.18E-3/251/4.66E-3/
 MASSP/35/6.02E-3/243/6.47E-3/
 MASSP/244/5.56E-3/245/5.63E-3/36/6.02E-3/

\$ GENERATE MASS LOADINGS FOR -X PANEL

MASSP/41/3.49E-3/256/4.66E-3/257/3.49E-3/
 MASSP/258/4.14E-3/42/5.43E-3/
 MASSP/260/1.87E-2/431/1.93E-2/
 MASSP/432/6.66E-3/433/6.28E-3/262/4.08E-3/
 MASSP/259/1.87E-2/429/2.11E-2/430/6.66E-3/
 MASSP/431/6.28E-3/261/4.08E-3/39/5.3E-3/253/2.85E-3/
 MASSP/253/2.85E-3/254/3.49E-3/255/4.14E-3/40/5.43E-3/

\$ GENERATE MASS LOADINGS FOR -Y PANEL

MASSP/44/6.3E-3/265/5.91E-3/264/5.85E-3/
 MASSP/263/6.75E-3/43/8.11E-3/271/4.94E-3/
 MASSP/437/7.47E-3/436/1.25E-2/435/1.25E-2/
 MASSP/269/4.94E-3/272/4.94E-3/440/7.47E-3/
 MASSP/439/1.25E-2/438/1.25E-2/270/4.94E-3/
 MASSP/46/6.3E-3/268/5.91E-3/267/5.85E-3/
 MASSP/266/8.57E-3/45/6.3E-3/

\$ GENERATE MASS LOADINGS FOR +X PANEL

MASSP/48/5.14E-3/275/4.79E-3/274/3.45E-3/
 MASSP/273/2.55E-3/47/4.79E-3/281/3.78E-3/
 MASSP/443/5.98E-3/442/8.18E-3/441/3.78E-3/
 MASSP/279/4.79E-3/282/3.78E-3/446/5.07E-3/
 MASSP/445/8.18E-3/444/3.71E-3/280/3.78E-3/
 MASSP/50/5.14E-3/278/4.79E-3/277/3.84E-3/
 MASSP/276/2.48E-3/49/3.78E-3/

\$ GENERATES GRID MASS FOR SOLAR PANELS

\$ SURFACE MOUNT SOLAR PANELS

MASSG/A+Y/1.531815E-5,1.531815E-5,1.531815E-5,1.531815E-5/
 MASSG/A-Y/1.531815E-5,1.531815E-5,1.531815E-5,1.531815E-5/
 MASSG/B+Y/2.402E-5,2.402E-5,2.402E-5,2.402E-5/
 MASSG/B-Y/2.402E-5,2.402E-5,2.402E-5,2.402E-5/
 MASSG/A+X/1.196E-5,1.196E-5,1.196E-5,1.196E-5/
 MASSG/A-X/1.196E-5,1.196E-5,1.196E-5,1.196E-5/
 MASSG/B+X/1.8755E-5,1.8755E-5,1.8755E-5,1.8755E-5/
 MASSG/B-X/1.8755E-5,1.8755E-5,1.8755E-5,1.8755E-5/
 MASSG/C+X/1.8076E-5,1.8076E-5,1.8076E-5,1.8076E-5/
 MASSG/C-X/1.8076E-5,1.8076E-5,1.8076E-5,1.8076E-5/

\$ DEPLOYED SOLAR PANELS

MASSG/D+X/6.343E-6,6.343E-6,6.343E-6,6.343E-6/
 MASSG/D-X/6.343E-6,6.343E-6,6.343E-6,6.343E-6/
 MASSG/D+Y/6.343E-6,6.343E-6,6.343E-6,6.343E-6/
 MASSG/D-Y/6.343E-6,6.343E-6,6.343E-6,6.343E-6/

\$ DETERMINES MISCELLANEOUS UNACCOUNTED MASS

\$ DISTRIBUTED OVER SPACECRAFT PANELS

\$ A-PANELS

MASSG/A+X/1.4691E-5,1.4691E-5,1.4691E-5,1.4691E-5/
MASSG/A-X/1.4691E-5,1.4691E-5,1.4691E-5,1.4691E-5/
MASSG/A+Y/1.4691E-5,1.4691E-5,1.4691E-5,1.4691E-5/
MASSG/A-Y/1.4691E-5,1.4691E-5,1.4691E-5,1.4691E-5/

\$ B-PANELS

MASSG/B+X/2.303662E-5,2.303662E-5,2.303662E-5,2.303662E-5/
MASSG/B-X/2.303662E-5,2.303662E-5,2.303662E-5,2.303662E-5/
MASSG/B+Y/2.303662E-5,2.303662E-5,2.303662E-5,2.303662E-5/
MASSG/B-Y/2.303662E-5,2.303662E-5,2.303662E-5,2.303662E-5/

\$ C-PANELS

MASSG/C+X/2.220272E-5,2.220272E-5,2.220272E-5,2.220272E-5/
MASSG/C-X/2.220272E-5,2.220272E-5,2.220272E-5,2.220272E-5/

\$ TOP PANEL

MASSG/ZL/5.897597E-6,5.897597E-6,5.897597E-6,5.897597E-6/
MASSG/ZR/5.897597E-6,5.897597E-6,5.897597E-6,5.897597E-6/

\$ RF PANEL

MASSG/RF/1.226228E-5,1.226228E-5,1.226228E-5,1.226228E-5/

\$ BOTTOM PANEL

MASSG/BOTTOM/1.179519E-5,1.179519E-5,1.179519E-5,1.179519E-5/

END

APPENDIX D

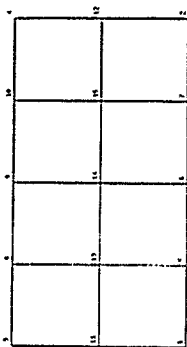
A PANEL (A-X)

GRID DESCRIPTION

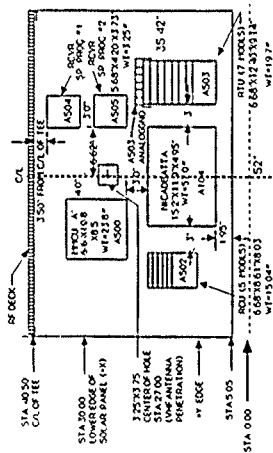
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A PANEL (A+X)

GRID DESCRIPTION



COMPONENT PLACEMENT



PANEL (A-X)

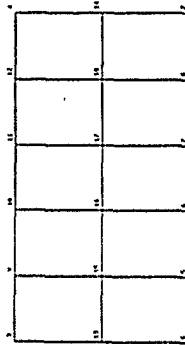
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MCU A	238
RTU	197
RCU	1504
DCVR SP PROC A	325
RCVR SP PROC B	325
PANEL SUBSTRATE	262
WADNESS (ESTIMATE)	7200
TOTAL	16824

Weight Distribution by Point (lbs)

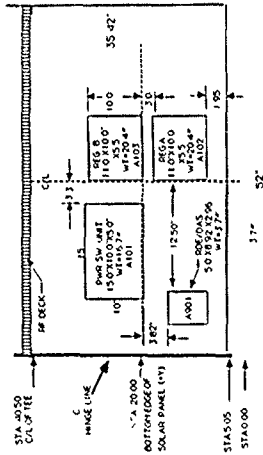
pt.	ut.	pt.	ut.	pt.	ut.	pt.	ut.
3	1.33	8	7.28	9	8.91	10	2.96
11	5.09	13	18.17	14	23.16	15	15.02
1	5.09	5	12.22	6	15.58	7	13.39
							2
							6.26

A PANEL (A+Y)

GRID DESCRIPTION



COMPONENT PLACEMENT



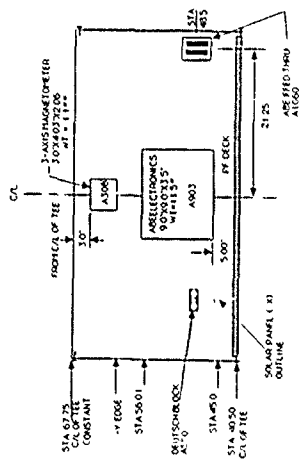
PANEL (A-Y)

weight	
PEG UNIT ALO	40.0
DWA SW ALO	16.7
PRODAAACQSYS	3.7
PANELSUBSTRATE	27.2
WADRESS (ESTIMATE)?	20.0
TOTAL	109.4

Weight Distribution by Point (lbs)

Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.
3	1.11	9	5.28	10	7.84	11	6.21	12	3.66	4	1.11
13	2.04	15	6.21	16	10.4	17	11.31	18	6.21	14	1.11
1	2.04	5	2.04	6	3.66	7	6.21	8	3.66	2	1.11

COMPONENT PLACEMENT

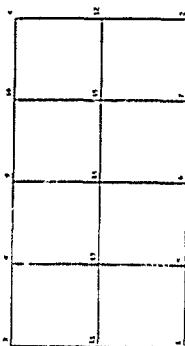


PANEL (B-X)

WEIGHT	
MAGNETOMETER	1.14
MAGNETOMETER	15.64
MAGNETOMETER	1.14
MAGNETOMETER	2.0
MAGNETOMETER (ESTIMATE)	2.0
TOTAL	39.72

B PANEL (B-X)

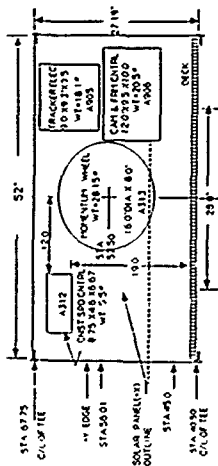
GRID DESCRIPTION



Weight Distribution by Point (lbs)

Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.
3	-	8	-	9	.836	10	-	4	-
11	-	13	2.89	14	3.44	15	2.89	12	-
1	-	5	2.89	6	2.89	7	2.89	2	-

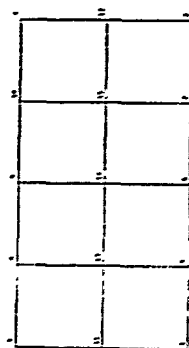
COMPONENT PLACEMENT



PANEL (B-X)

WEIGHT	
FWA	28.15"
CONST-SPEECH	53
WATER T.C.	18
CABLE FRICION	20.5
PANEL STRAITE	31.1
MOORE 25157 (P/12)	40
TOTAL	97.35"

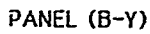
GRID DESCRIPTION



B PANEL (B-X)

Weight Distribution by Point (lbs)

Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.
3	1.65	8	3.41	9	3.79	10	6.56	4	4.6
11	1.65	13	5.17	14	7.31	15	13.44	12	9.93
1	.267	5	2.03	6	3.79	7	6.91	2	5.39



PANELSUBSTRATE 206

TOTAL	206
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GRID DESCRIPTION

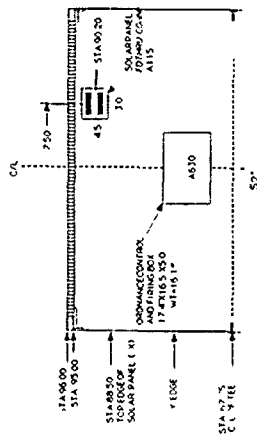
143

Weight Distribution by Point (lbs)

PT.	WT.	PT.	WT.	PT.	WT.	PT.	WT.	PT.	WT.	PT.	WT.
3	-	9	-	10	-	11	-	12	-	4	-
13	3.25	15	3.25	16	13.15	17	7.0	18	6.15	14	-
1	3.25	5	3.25	6	13.15	7	6.15	8	2	2	-

COMPONENT PLACEMENT

GRID DESCRIPTION



PANEL (C-X)

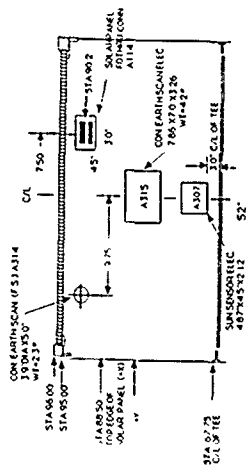
WEIGHT	
ORDNANCE CONTROL BOX	16.1*
SOLAR PANEL FEED THRU	16.1*
CONNECTION	20.8*
PANEL SUBSTRATE	40.0*
ADDRESS (ESTIMATE)	
TOTAL	40.9*

C PANEL (C-X)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	1014	1015	1016	1017	1018	1019	1020	1021	1022	1023	1024	1025	1026	1027	1028	1029	1030	1031	1032	1033	1034	1035	1036	1037	1038	1039	1040	1041	1042	1043	1044	1045	1046	1047	1048	1049	1050	1051	1052	1053	1054	1055	1056	1057	1058	1059	1060	1061	1062	1063	1064	1065	1066	1067	1068	1069	1070	1071	1072	1073	1074	1075	1076	1077	1078	1079	1080	1081	1082	1083	1084	1085	1086	1087	1088	1089	1090	1091	1092	1093	1094	1095	1096	1097	1098	1099	1100	1101	1102	1103	1104	1105	1106	1107	1108	1109	1110	1111	1112	1113	1114	1115	1116	1117	1118	1119	1120	1121	1122	1123	1124	1125	1126	1127	1128	1129	1130	1131	1132	1133	1134	1135	1136	1137	1138	1139	1140	1141	1142	1143	1144	1145	1146	1147	1148	1149	1150	1151	1152	1153	1154	1155	1156	1157	1158	1159	1160	1161	1162	1163	1164	1165	1166	1167	1168	1169	1170	1171	1172	1173	1174	1175	1176	1177	1178	1179	1180	1181	1182	1183	1184	1185	1186	1187	1188	1189	1190	1191	1192	1193	1194	1195	1196	1197	1198	1199	1200	1201	1202	1203	1204	1205	1206	1207	1208	1209	1210	1211	1212	1213	1214	1215	1216	1217	1218	1219	1220	1221	12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C PANEL (C+X)

COMPONENT PLACEMENT¹



PANEL (C-X)

WEIGHT	
SUNSENSE ELECTRONICS	133
CON EARTHSCAN	23*
CON EARTHSCAN/EC	42*
PAN/ESTIMATE	207
MAN/ESS (EST)	10
TOTAL	29.53*

GRID DESCRIPTION[illegible]

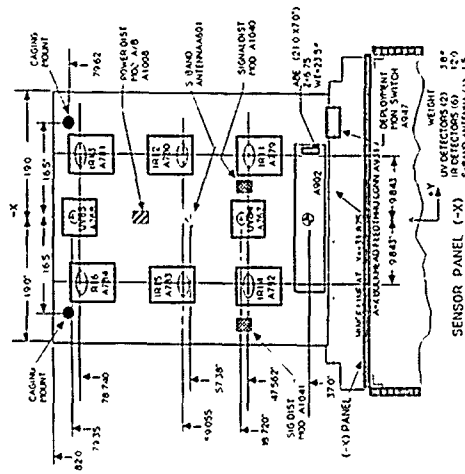
Weight Distribution by Point (lbs)

PT.	WT.	PT.	WT.	PT.	WT.
8	1.29	9	-	10	-
28	1.29	29	-	30	-
25	-	26	1.19	27	1.19
22	-	23	1.19	24	1.19
19	-	20	1.47	21	-

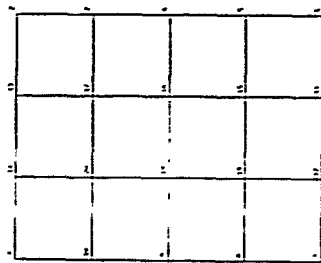
All other points are zero

SENSOR PANEL (-X)

COMPONENT PLACEMENT



GRID DESCRIPTION



Weight Distribution by Point (lbs)

	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.
	4	2.1	14	1.58	13	1.58	2	2.1
	10	1.6	20	2.42	17	2.42	7	1.6
	9	1.35	19	2.58	16	2.58	6	1.35
	8	1.8	18	7.45	15	8.15	5	1.1
	3	1.35	12	7.22	11	7.22	1	2.05

SENSOR PANEL (+X)

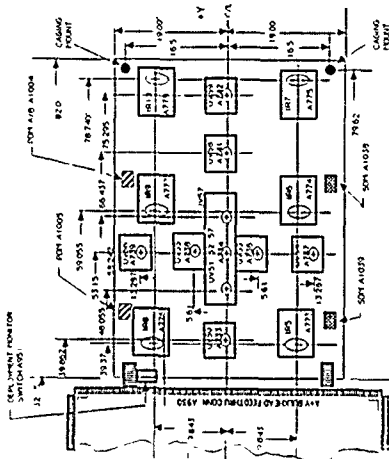
GRID DESCRIPTION

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SENSOR PANEL (-Y)

GRID DESCRIPTION

COMPONENT PLACEMENT



SENSOR PANEL (•Y)

WEIGHT	
UV DETECTORS (17)	1330
UV 3 PAC (15)	60
IR DETEC (15)(6)	21
POWER ONST	120
MODULES (1)	20
SIGNAL DISY	
MODULES (2)	14
PANEL SUBSTRATE	2254
CABLES AND WIRAGES	40
WADNESS	165
TOTAL	2764*

SS - POWER CRST
MODULE (POM)

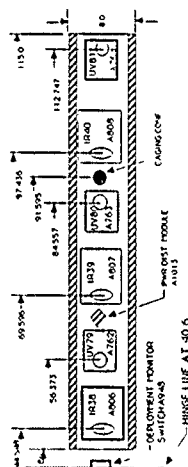
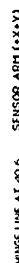
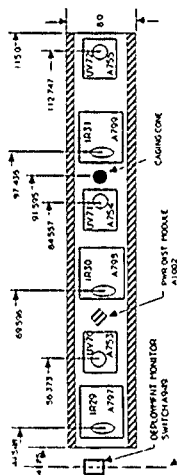
SS - SIGNAL CRST
MODULE (SOM)

Weight Distribution by Point (lbs)

Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.
3	2.44	8	2.28	9	2.26	10	2.61	4	3.14
12	1.91	18	2.88	19	4.84	20	4.84	14	1.91
11	1.91	15	2.88	16	4.84	17	4.84	13	1.91
1	2.44	5	2.28	6	2.26	7	3.31	2	2.44

150

POINT DESIGNATION



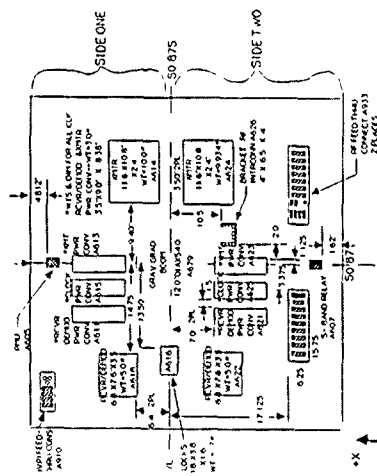
SENSOR ARM (X-Y)

WEIGHT (FOR EACH ARM)	5.7*
UV-RADIOTE DETECTORS (3)	6.0
IR REMOTE DETECTORS (3)	7
POWER DIST. MODULES (3)	10.0
SENSOR ARM	6.9
MASSNESS	
TOTAL	29.3*

Weight Distribution by Point (lbs)

Pt.	Wt.
1	3.15
2	3.09
3	4.33
4	3.09
5	3.15
6	3.09

GRID DESCRIPTION



RF DECK

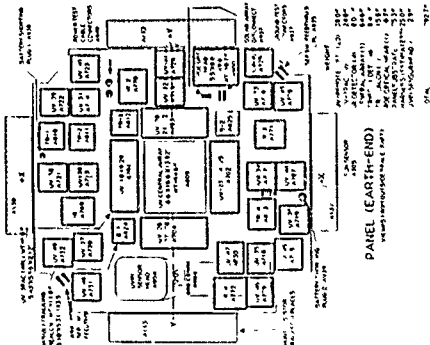
	WEIGHT	R#	DECK
PAPER(S) (2)	10934 ⁴⁰		
PRINTED P.S. (2)	80		
ACTIVE/CLOCK(S) (2)	10306		
ICVMS P.S. (2)	60		
STAMPAL CLOCK (1)	781		
CLOCK P.S. (2)	60		
WPS	26		
PPS	11		
DAMEL SUBSTRATE	32035		
HARDNESS TESTIMATE(???)	250		
TOTAL			

Weight Distribution by Point (lbs)

Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.
3	.833	8	.833	9	.97	10	.833	4	.833
14	2.12	28	4.98	29	3.22	30	.833	18	.833
13	2.32	25	4.56	26	6.41	27	4.13	17	4.13
12	2.32	22	3.82	23	8.96	24	7.46	16	7.46
11	2.12	19	3.62	20	5.64	21	4.13	15	4.13
1	.833	5	2.33	6	2.44	7	.835	2	.835

EARTH END PANEL

COMPONENT PLACEMENT



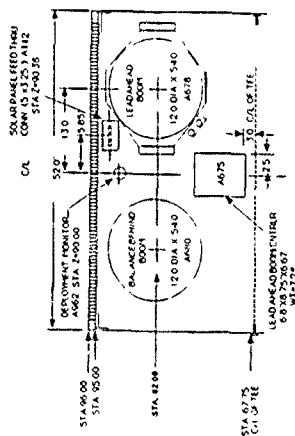
GRID DESCRIPTION

5	14	25	36	47
6	25	36	47	58
7	36	47	58	69
8	47	58	69	80
9	58	69	80	91
10	69	80	91	102
11	80	91	102	113
12	91	102	113	124
13	102	113	124	135
14	113	124	135	146
15	124	135	146	157
16	135	146	157	168
17	146	157	168	179
18	157	168	179	190
19	168	179	190	201
20	179	190	201	212

Weight Distribution by Point (lbs)

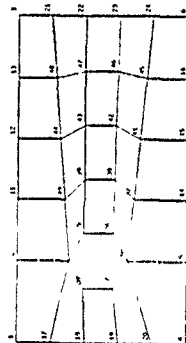
	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.
3	3	2.26	8	3.73	9	4.12	10	3.23	4	2.26						
14	14	12.34	28	14.57	29	6.76	30	8.63	18	4.93						
13	13	10.92	25	21.24	26	23.46	27	16.76	17	4.46						
12	12	9.94	22	22.24	23	23.98	24	13.13	16	2.28						
11	11	11.36	19	14.59	20	7.33	21	6.03	15	2.76						
1	1	2.26	5	2.76	6	3.33	7	4.26	2	2.27						

GRID DESCRIPTION



PANEL (C·Y)

WEIGHT	
LEADHEAD	72°
DOOR/CENTRAL	196
PANEL/SUBSTRATE	20
TOTAL	292°



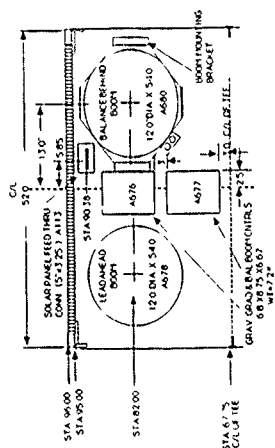
Weight Distribution by Point (lbs)

Pt.	Wt.	Pt.	Wt.
38	1.53	42	1.53
37	1.53	41	1.53
14	4.53	15	1.53

All other points are zero

	All other points are zero
--	---------------------------

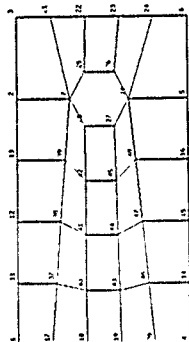
COMPONENT PLACEMENT



PANEL (C-Y)

WEIGHT	
BALANCE	72"
BOOFTONER	72"
GRAYGLAD	72"
BOOFTONER	72"
HARKISS	170"
PANEL SUBSTRATE	170"
TOTAL	394"

GRID DESCRIPTION

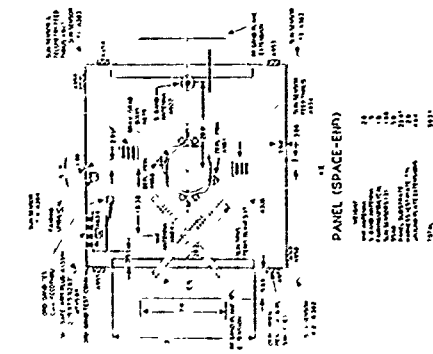


PANEL C (C-Y)

Weight Distribution by Point (lbs)

Pt.	Wt.	Pt.	Wt.
38	1.87	39	1.87
41	1.87	42	1.87
44	3.74	45	3.74
47	1.87	48	1.87
15	1.87	16	1.87

GRID DESCRIPTION



Weight Distribution by Point (lbm)

Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.	Pt.	Wt.
1	2.04	11	1.63	2	1.30	-	-	12	.30	3	.60
15	2.2	35	1.63	7	.30	-	-	42	.30	19	.96
16	1.66	36	.9	26	.30	23	.31	41	.30	20	2.33
17	1.66	37	.80	25	.30	24	.30	40	.30	21	1.33
18	.96	38	.38	10	.30	-	-	39	.31	22	.96
4	.8	13	.38	5	.30	-	-	14	.30	6	.80

APPENDIX E

! COM FILE TO GENERATE 150' TRUSS AS A SUBSTRUCTURE TO BE
! ATTACHED TO THE MAIN BODY OF THE SPACECRAFT

\$ BEAMCS
TRUS150
OLB/TRUSCS
QUIT
\$ BULKM
TRUS150
OLB/TRS150BM
QUIT
\$ LOADBC
TRUS150
OLB/TRUSBC
OLB/TRSMAS15
QUIT
\$ BULKF
TRUS150
1///
\$ DEFCS
TRUS150
6
1,2,3,4,5,6
OLB/TRUSDEF
QUIT
\$ ADSTIF
TRUS150
\$ STASS
TRUS150
\$ DECOM
TRUS150
\$ REDCS
TRUS150

! FILENAME IS TRUSCS.SRC

! GENERATES CROSS SECTION TYPE AND DIMENSION OF BEAM ELEMENTS

CIRCS/8/.075/END

! BULKM FILE THAT GENERATES 150' TRUSS

! FILENAME IS TRUS150BM.SRC

```

ELMAT,4/6/6.0E4,8.0E6,.29,1.940994E-4/
KPOINT/1/0,0,4.763/2/0,8.25,0/3/0,0,-4.763/4/1800,0,4.763/
KPOINT/5/1800,8.25,0/6/1800,0,-4.763/7/90,0,50/
LETY/BEAM2/6,8/
SLINE,10/L14/1,4,301/7/L36/3,6,301/7/L25/2,5,301/8/L12/1,2,3
/7/
SLINE,10/L23/2,3,3/7/L13/1,3,3/7/L45/4,5,3/7/L56/5,6,3/7/
SLINE,10/L46/4,6,3/7/
END

```

! EDITM FILE TO ADD BATTENS AND DIAGONALS TO THE 150' TRUSS

! FILENAME IS TRS150EM.SRC

PTRTH/8/PTRTM/6/

\$ VERTICAL MEMBERS

BEAM2/9,307,7,149/157,455,7/158,307,7,149/306,455,7/

\$ BOTTOM MEMBERS

BEAM2/9,158,7,149/157,306,7/

\$ DIAGONAL MEMBERS

```

ETH,1/9/.001963/
PTRTH/9/
ROD2/9,159,148/156,306/10,158,148/157,305/9,308,148/156,455/
ROD2/10,307,148/157,454/158,308,148/305,455/159,307,148/306,
454/
ROD2/1,307/2,9/3,9/1,158/3,307/2,158/4,455/5,157/5,306/6,455/
ROD2/6,157/4,306/
END

```

! GENERATES POINT MASSES FOR THE 150' TRUSS

! FILENAME IS TRSMAS15.SRC

```

MASSP/1/2.71E-5/2/2.71E-5/3/2.71E-5/
MASSP/4/2.71E-5/5/2.71E-5/6/2.71E-5/
MASSP/9,307,299/2.71E-5,2.71E-5/308,606,299/2.71E-5,2.71E-5/
MASSP/607,905,299/2.71E-5,2.71E-5/
END

```

POINT	MASS X	MASS Y	MASS Z
440	1.234E-02	1.234E-02	1.234E-02
441	8.650E-03	8.650E-03	8.650E-03
442	1.305E-02	1.305E-02	1.305E-02
443	1.085E-02	1.085E-02	1.085E-02
444	8.580E-03	8.580E-03	8.580E-03
445	1.305E-02	-1.987E+00	1.305E-02
446	9.940E-03	4.594E-02	9.940E-03
447	1.842E-02	1.842E-02	-1.583E-03
448	1.842E-02	1.842E-02	1.842E-02
449	-6.583E-03	1.842E-02	1.842E-02
450	1.842E-02	1.842E-02	1.842E-02

APPENDIX F

\$! COM FILE TO GENERATE AND CONNECT SPACECRAFT TRUSSES

\$! FILENAME IS TRUSS.COM

DEL TRUSS.*;*

\$ BEAMCS

LACE

OLB/TRUSCS

QUIT

\$BULKM

LACE

OLB/TRUSSBM

QUIT

\$ EDITM

LACE

OLB/TRUSSEM

QUIT

\$ LOADBC

LACE

OLB/TRUSMASS

QUIT

\$ GENERATES THE FILE FOR THE THREE TRUSSES OF THE LACE

\$ SPACECRAFT USING THE PROCESSOR BULKM

\$ BULKM FILE TO GENERATE 150 FOOT TRUSS IN +Y DIRECTION

\$ ELEMENT MATERIAL

ELMAT,4/6/6.0E4,8.0E6,.29,1.94099E-4/

KPOINT/451/8.237,26,79.25/452/8.237,1826,79.25/

KPOINT/453/13,26,87.5/454/13,1826,87.5/

KPOINT/455/17.763,26,79.25/456/17.763,1826,79.25/

KPOINT/457/67.763,926,79.25/

LETY/BEAM2/6,8/

SLINE,10/LTR12/451,452,301/457/LTR34/453,454,301/457/

SLINE,10/LTR56/455,456,301/457/LTR13/451,453,3/457/

SLINE,10/LTR35/453,455,3/457/LTR15/451,455,3/457/

SLINE,10/LTR24/452,454,3/457/LTR46/454,456,3/457/

SLINE,10/LTR26/452,456,3/457/

\$ FILE TO GENERATE 150 FOOT TRUSS IN +Z DIRECTION

\$ ELEMENT MATERIAL

ELMAT,4/6/6.0E4,8.0E6,.29,1.94099E-4/

KPOINT/458/2.75,4.763,96/460/-5.5,0,96/
KPOINT/462/2.75,-4.763,96/459/2.75,4.763,1896/
KPOINT/461/-5.5,0,1896/463/2.75,-4.763,1896/
KPOINT/470/52.75,0,996/

LETY/BEAM2/6,8/

SLINE,10/LTR89/458,459,301/470/LTR6263/462,463,301/470/
SLINE,10/LTR01/460,461,301/470/LTR5860/458,460,3/470/
SLINE,10/LTR6062/460,462,3/470/LTR5862/458,462,3/470/
SLINE,10/LTR5961/459,461,3/470/LTR6163/461,463,3/470/
SLINE,10/LTR5963/459,463,3/470/

\$ GENERATES A FILE TO CONNECT 75 FOOT -Y-TRUSS BOOMS TO
\$ MAIN SPACECRAFT

KPOINT/464/-17.763,-26,79.25/
KPOINT/466/-13,-26,87.5/
KPOINT/468/-8.237,-26,79.25/
KPOINT/465/-17.763,-926,79.25/
KPOINT/467/-13,-926,87.5/
KPOINT/469/-8.237,-926,79.25/
KPOINT/471/67.763,-463,79.25/

LETY/BEAM2/6,8/

SLINE,10/L46869/468,469,151/471/L46465/464,465,151/471/
SLINE,10/L46667/466,467,151/471/L46567/465,467,3/471/
SLINE,10/L46769/467,469,3/471/L46569/465,469,3/471/
SLINE,10/L46466/464,466,3/471/L46668/466,468,3/471/
SLINE,10/L46468/464,468,3/471/

END

\$ GENERATES BATTENS AND DIAGONALS FOR SPACECRAFT TRUSS
\$ USING THE PROCESSOR EDITM

\$ FILENAME IS TRUSSEM.SRC

\$ THIS FILE MERGES THE TRUSSES TO THE SPACECRAFT

MERGE/546/451/19/453/549/455/
MERGE/557/548/31/461/553/462/
MERGE/550/464/25/466/553/468/

\$ GENERATES VERTICAL,BOTTOM,DIAGONAL MEMBERS FOR 150 FT TRUSS
\$ IN THE +Y DIRECTION

PTRTH/8
PTRM/6

\$ VERTICAL/BOTTOM MEMBERS

BEAM2/974,1273,457,299/1272,1571,457/
BEAM2/675,974,457,299/973,1272,457/
BEAM2/675,1273,457,299/973,1571,457

\$ GENERATES BATTENS AND DIAGONALS FOR SPACECRAFT TRUSS
\$ USING THE PROCESSOR EDITM

\$ FILENAME IS TRUSSEM.SRC

\$ THIS FILE MERGES THE TRUSSES TO THE SPACECRAFT

MERGE/546/451/19/453/549/455/
MERGE/557/548/31/461/553/462/
MERGE/550/464/25/466/553/468/

\$ GENERATES VERTICAL,BOTTOM,DIAGONAL MEMBERS FOR 150 FT TRUSS
\$ IN THE +Y DIRECTION

PTRTH/8
PTRM/6

\$ VERTICAL/BOTTOM MEMBERS

BEAM2/974,1273,457,299/1272,1571,457/
BEAM2/675,974,457,299/973,1272,457/
BEAM2/675,1273,457,299/973,1571,457

\$ DIAGONAL MEMBERS

ETH,1/10/.001963/

PTRTH/10/

ROD2/455,675/451,1273/455,974/453,1273/453,675/451,974/
ROD2/975,1273,298/1272,1570/974,1274,298/1271,1571/
ROD2/675,975,298/972,1272/676,974,298/973,1271/
ROD2/675,1274,298/972,1571/676,1273,298/973,1570/
ROD2/456,973/452,1571/456,1272/454,1571/452,1272/454,973/

\$ GENERATES VERTICAL,BOTTOM,DIAGONAL MEMBERS FOR 150 FT TRUSS
\$ IN THE +Z DIRECTION

PTRTH/8

PTRM/6

\$ VERTICAL/BOTTOM MEMBERS

BEAM2/1578,1877,464,299/1876,2175,464/
BEAM2/1578,2176,464,299/1876,2474,464/
BEAM2/1877,2176,464,299/2175,2474,464

\$ DIAGONAL MEMBERS

ETH,1/10/.001963/

PTRTH/10/

ROD2/463,1876/459,2175/461,1876/459,2474/461,2175/463,2474/
ROD2/1877,2177,298/2174,2474/1878,2176,298/2175,2473/
ROD2/1579,1877,298/1876,2174/1578,1878,298/1875,2175/
ROD2/1579,2176,298/1876,2473/1578,2177,298/1875,2474/
ROD2/462,2176/462,1578/460,1877/460,1578/458,2176/458,1877/

\$ GENERATES VERTICAL,BOTTOM,DIAGONAL MEMBERS FOR 75 FT TRUSS
\$ IN THE -Y DIRECTION

PTRTH/8

PTRM/6

\$ VERTICAL/BOTTOM MEMBERS

BEAM2/2630,2779,470,149/2778,2927,470/
BEAM2/2481,2779,470,149/2629,2927,470/
BEAM2/2481,2630,470,149/2629,2778,470/

\$ DIAGONAL MEMBERS

ETH,1/10/.001963/

PTRTH/10/

ROD2/464,2779/466,2630/464,2481/468,2630/468,2779/466,2481/
ROD2/2630,2780,148/2777,2927/2631,2779,148/2778,2926/
ROD2/2482,2630,148/2629,2777/2481,2631,148/2628,2778/
ROD2/2481,2780,148/2628,2927/2482,2779,148/2629,2926/
ROD2/465,2927/467,2778/465,2629/469,2778/469,2927/467,2629/

END

\$ GENERATES MASS FOR THE COMPLETE TRUSS MODEL

\$ GENERATES MASS FOR THE 150 FOOT TRUSS IN +Y DIRECTION

MASSP/451/8.8846E-5/452/8.8846E-5/453/8.8846E-5/
MASSP/454/8.8846E-5/455/8.8846E-5/456/8.8846E-5/
MASSP/1273,1571,299/8.8846E-5,8.8846E-5/
MASSP/675,973,299/8.8846E-5,8.8846E-5/
MASSP/974,1272,299/8.8846E-5,8.8846E-5/

\$ GENERATES MASS FOR THE 150 FOOT TRUSS IN +Z DIRECTION

MASSP/464/8.8846E-5/465/8.8846E-5/466/8.8846E-5/
MASSP/467/8.8846E-5/468/8.8846E-5/469/8.8846E-5/
MASSP/2779,2927,149/8.8846E-5,8.8846E-5/
MASSP/2630,2778,149/8.8846E-5,8.8846E-5/
MASSP/2481,2629,149/8.8846E-5,8.8846E-5/

\$ GENERATES MASS FOR THE 75 FOOT TRUSS IN -Y DIRECTION

MASSP/458/8.8846E-5/459/8.8846E-5/460/8.8846E-5/
MASSP/461/8.8846E-5/462/8.8846E-5/463/8.8846E-5/
MASSP/1578,1876,299/8.8846E-5,8.8846E-5/
MASSP/1877,2175,299/8.8846E-5,8.8846E-5/
MASSP/2176,2474,299/8.8846E-5,8.8846E-5/

\$ GENERATES TIPMASS FOR EACH TRUSS

MASSP/459/1.72533E-1/461/1.72533E-1/463/1.72533E-1/
MASSP/452/3.0193E-2/454/3.0193E-2/456/3.0193E-2/
MASSP/465/3.0193E-2/467/3.0193E-2/469/3.0193E-2/

END

APPENDIX G

Before the LACE spacecraft was in its fully deployed state, it underwent three different configurations. Figures G1 to G4 show the natural frequencies and mode shapes of the LACE spacecraft in its initial configuration with the gravity gradient extended to 75 feet. Figures G5 to G8 show LACE with the gravity gradient extended to 150 feet. Figures G9 to G12 show the LACE spacecraft in its final configuration before full deployment with the lead and trail booms extended to 119.5 feet.

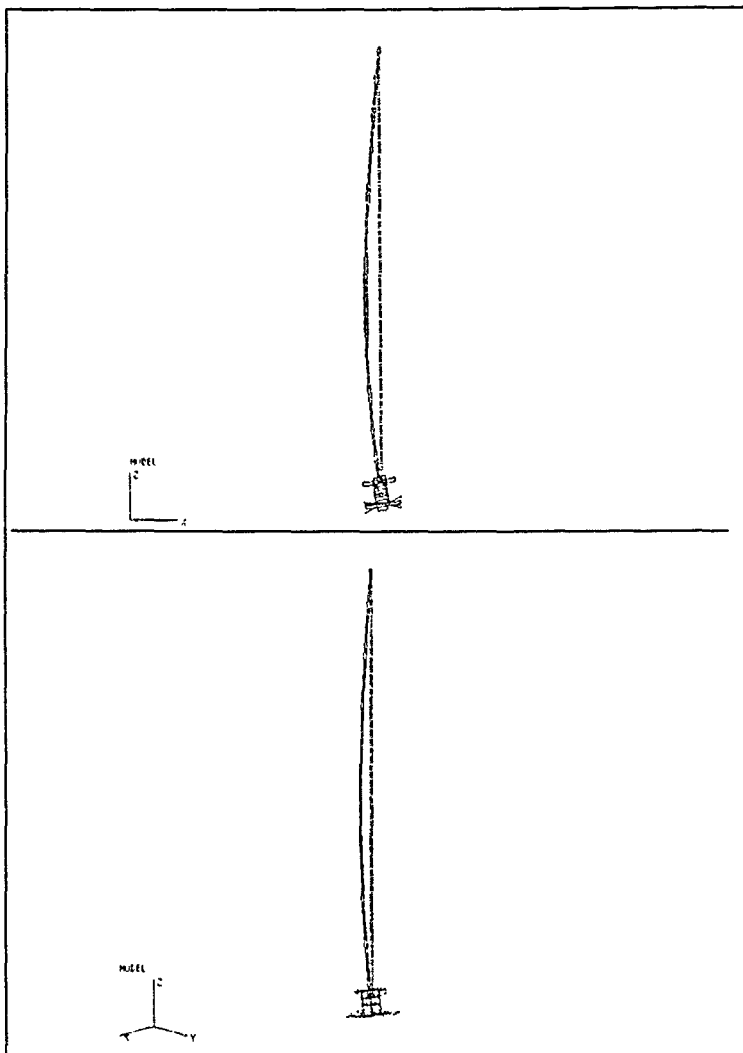


Figure G1. Mode 1, $\nu = .01365$ Hz, GIFTS COMPLEX MODEL

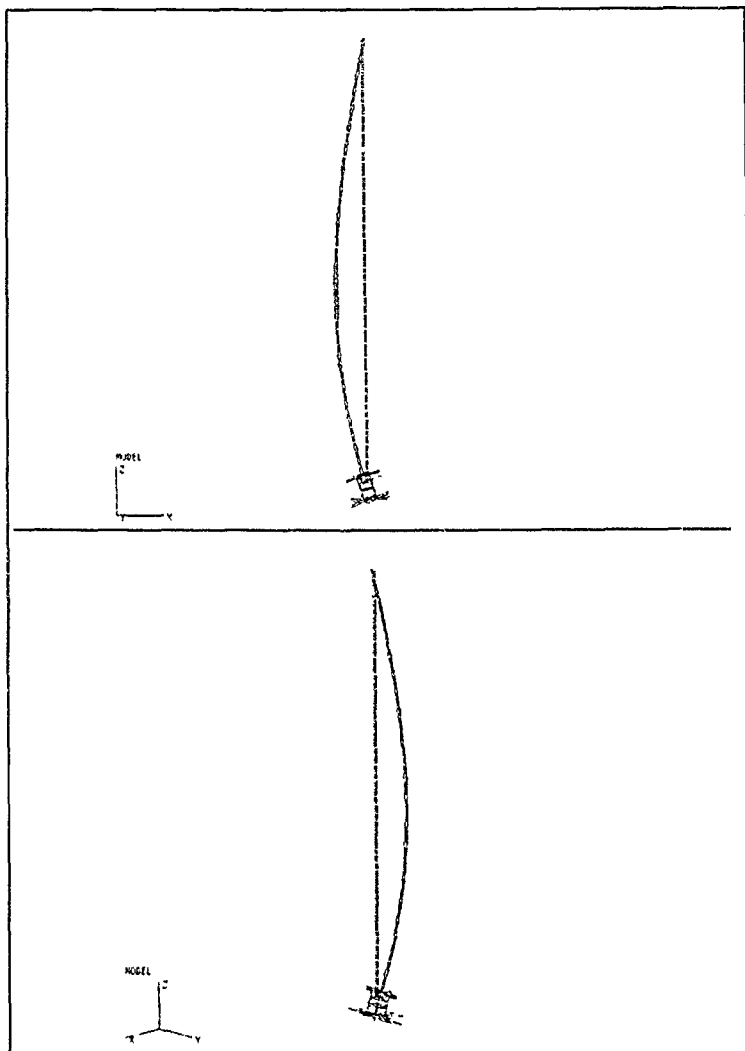


Figure G2. Mode 2, $\nu = .01379$ Hz, GIFTS COMPLEX MODEL

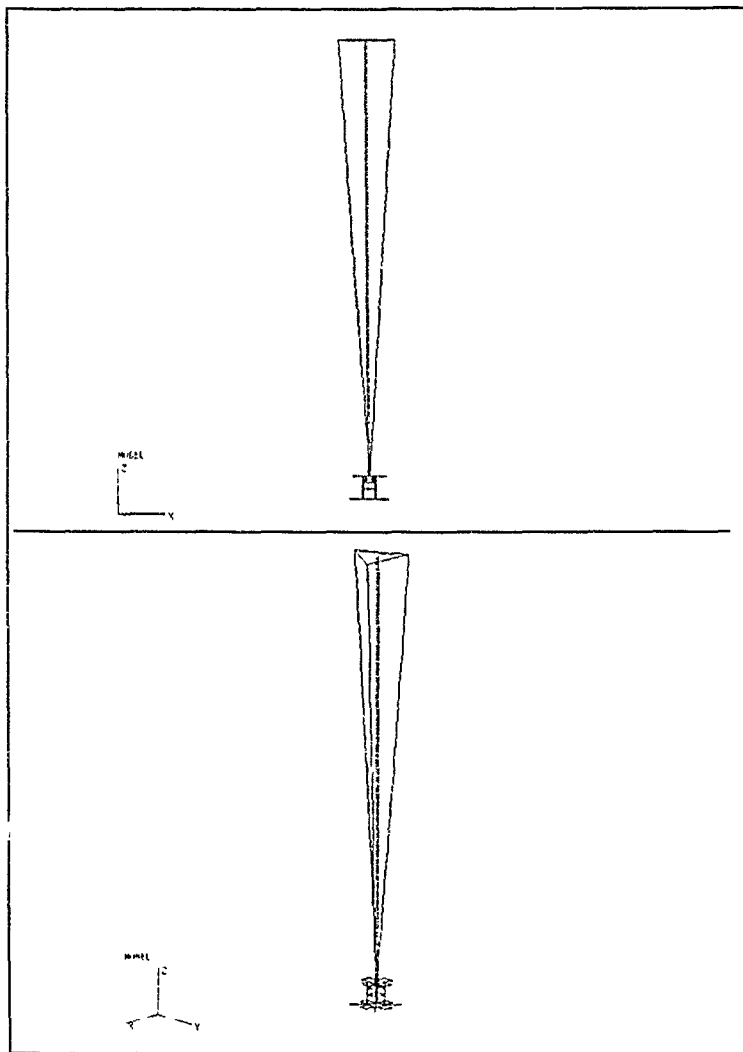


Figure G3. Mode 3, $\omega = .04325$ Hz, GIFTS COMPLEX MODEL

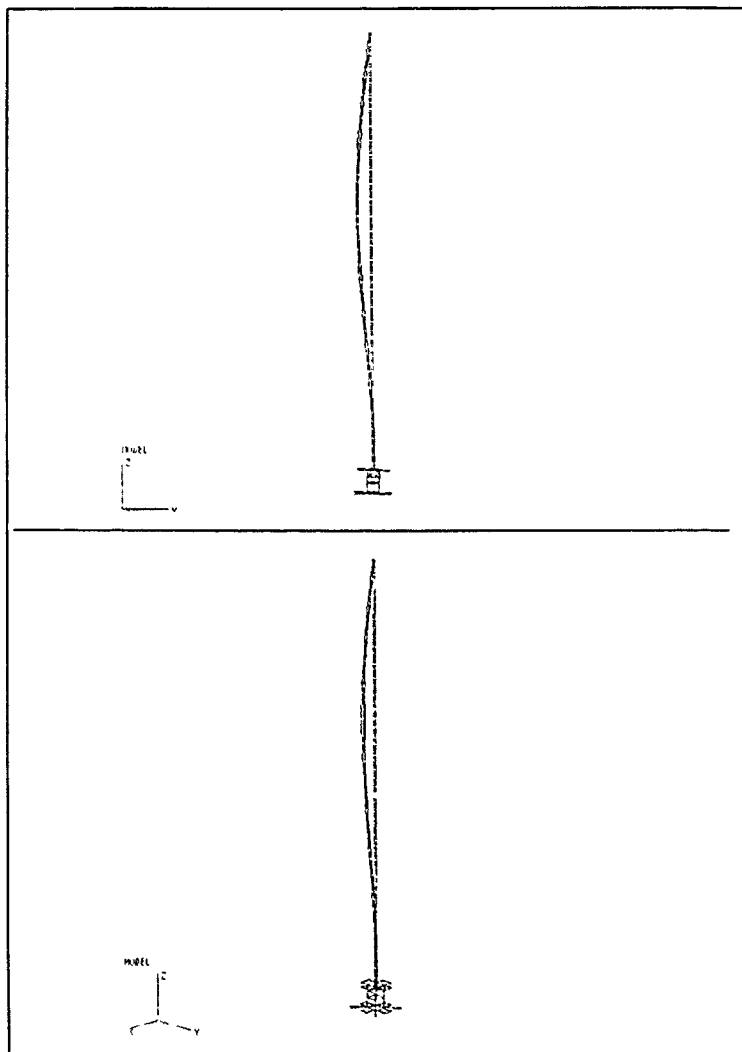


Figure G4. Mode 4, $\omega = .04579$ Hz, GIFTS COMPLEX MODEL

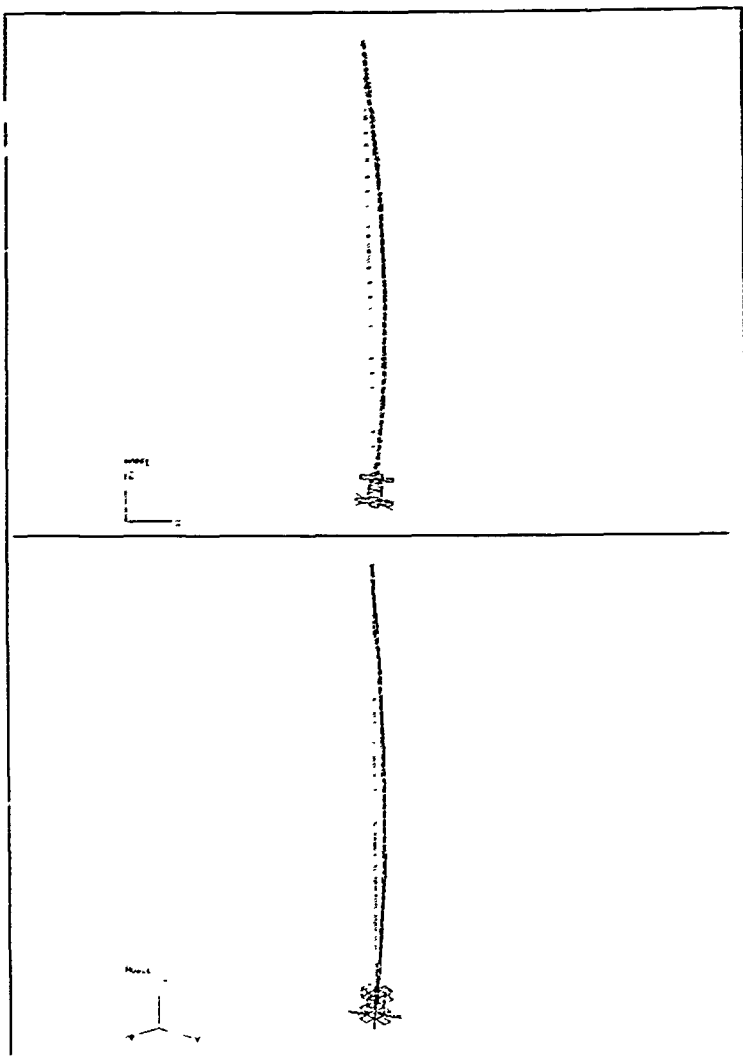


Figure G5. Mode 1, $\omega = .01217$ Hz, GIFTS COMPLEX MODEL

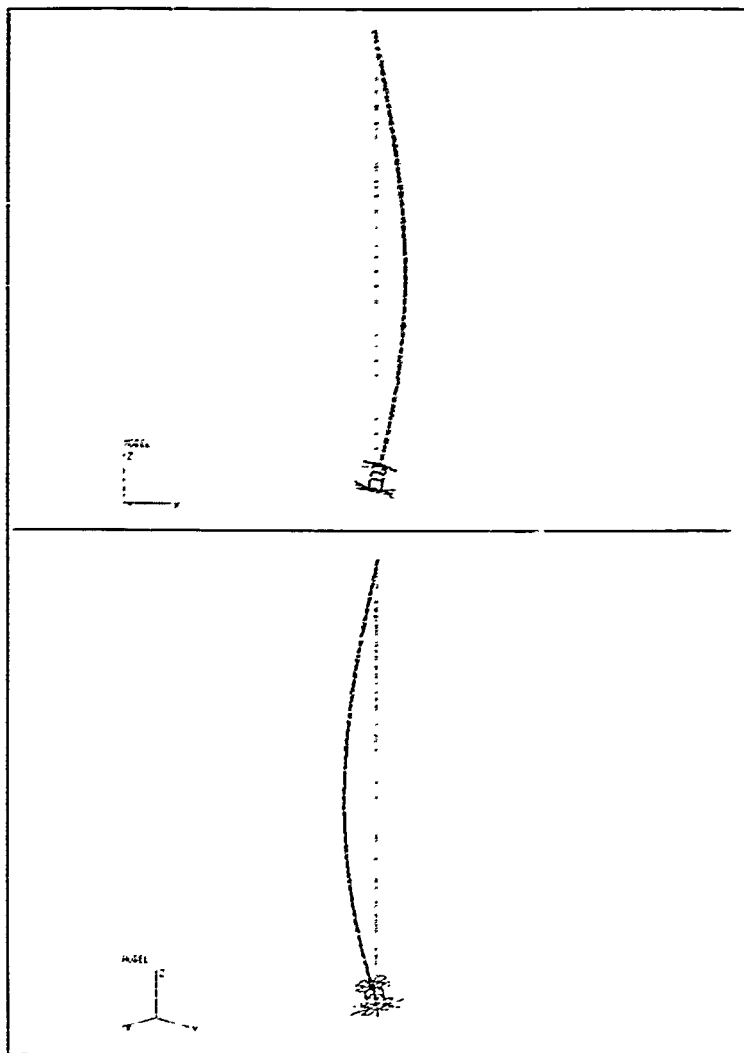


Figure G6. Mode 2, $\omega = .01226$ Hz, GIFTS COMPLEX MODEL

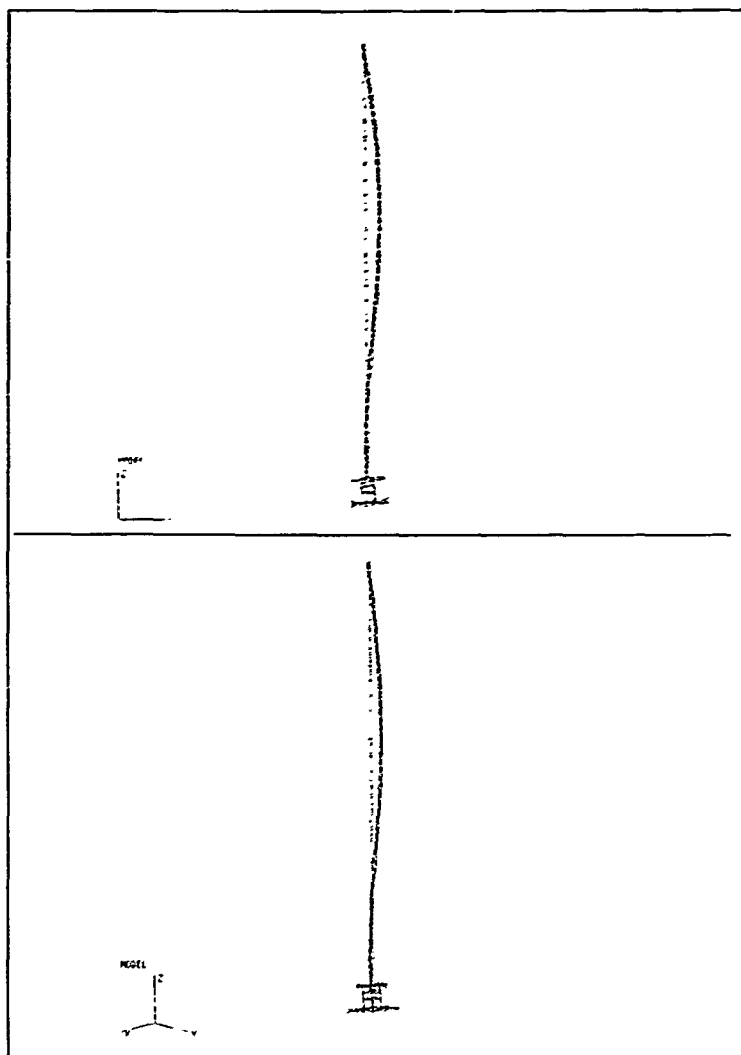


Figure G7. Mode 3, $\omega = .03535$ Hz, GIFTS COMPLEX MODEL

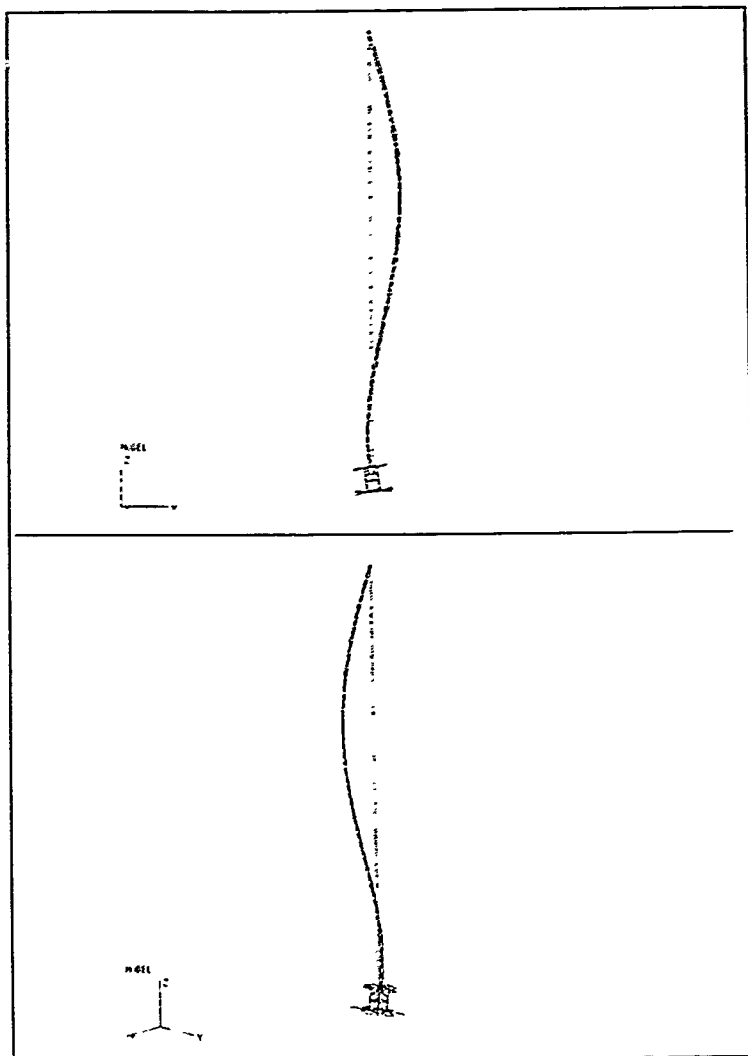


Figure G8. Mode 4, $\nu = .03552$ Hz, GIFTS COMPLEX MODEL

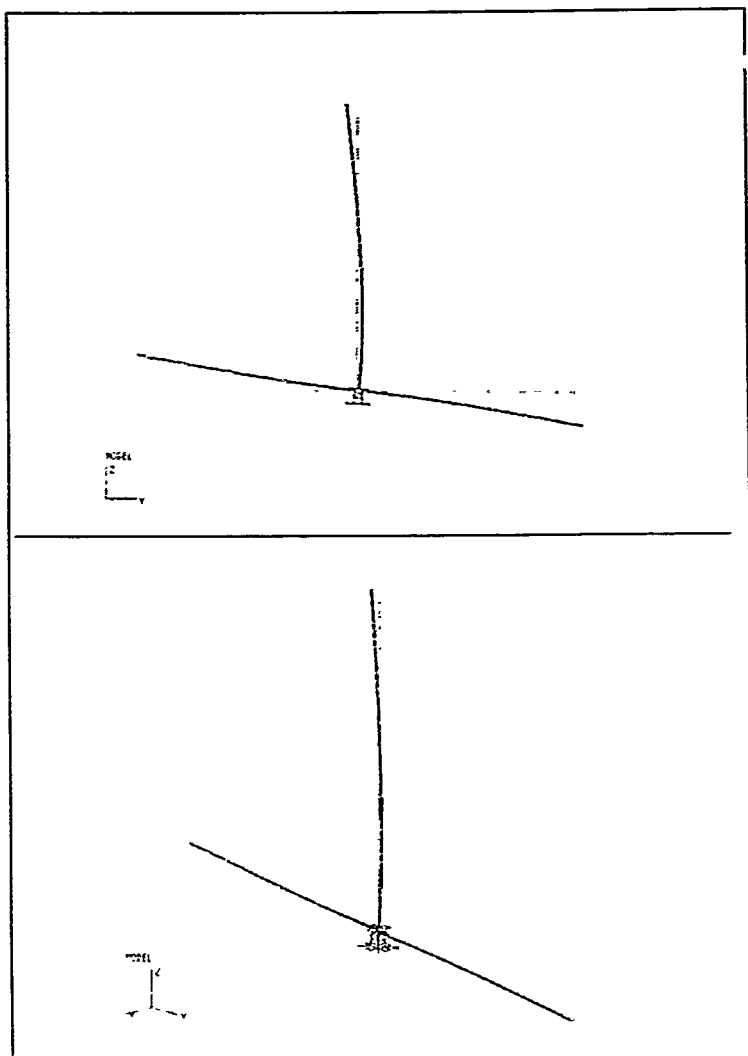


Figure G9. Mode 1, $\omega = .02322$ Hz, GIFTS COMPLEX MODEL

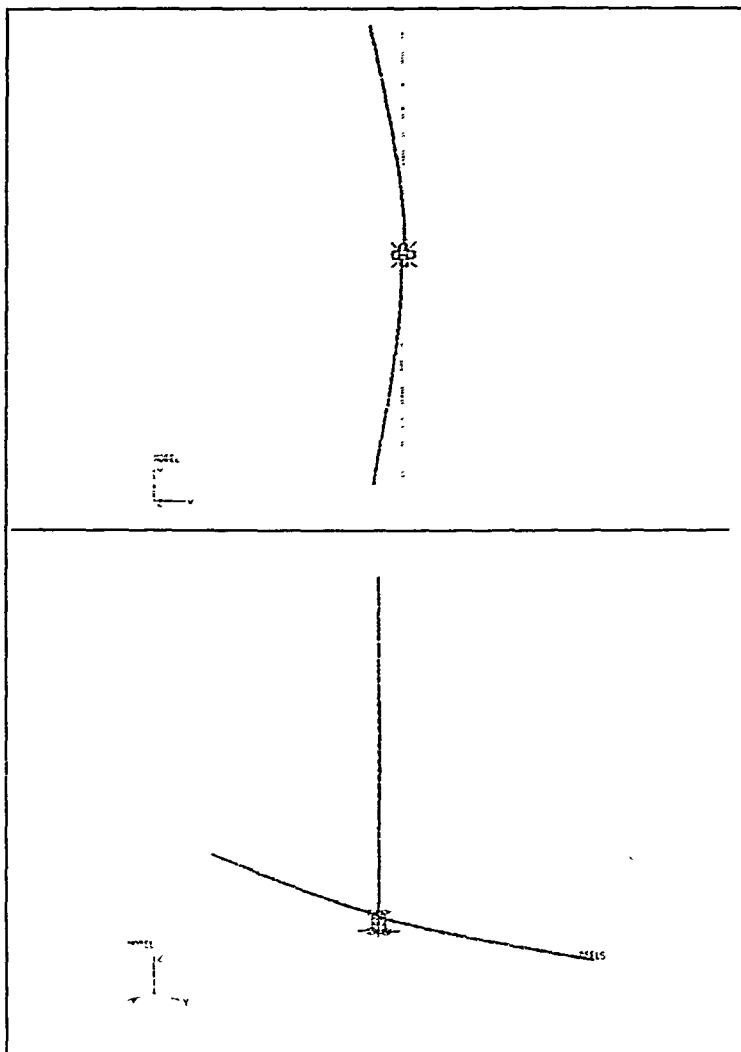


Figure G10. Mode 2, $\nu = .04294$ Hz, GIFTS COMPLEX MODEL

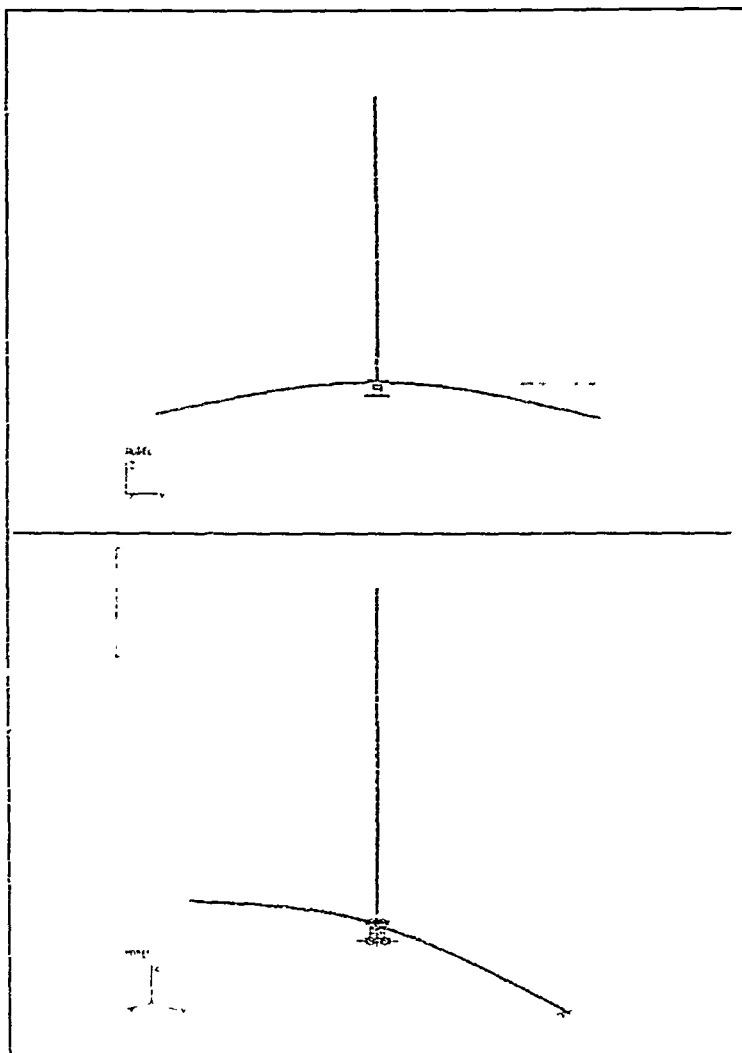


Figure G11. Mode 3, $\omega = .04302$ Hz, GIFTS COMPLEX MODEL

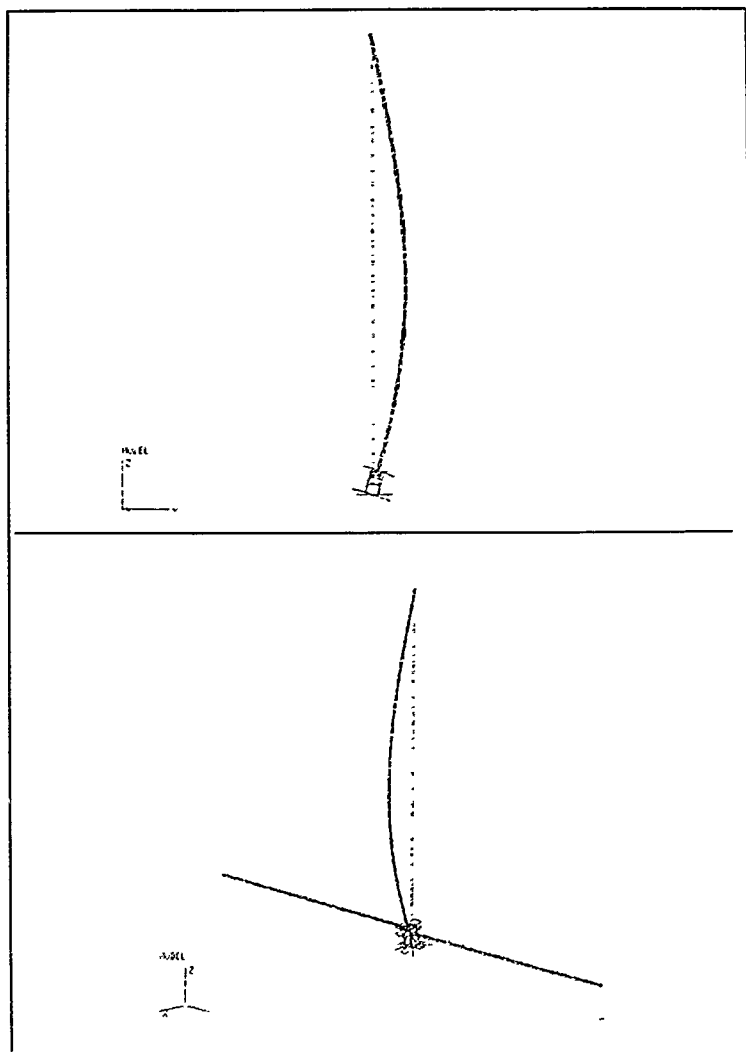


Figure G12. Mode 4, $\nu = .1349$ Hz, GIFTS COMPLEX MODEL

APPENDIX H

A. MAXIMUM TEMPERATURE FOR DIAGONALS

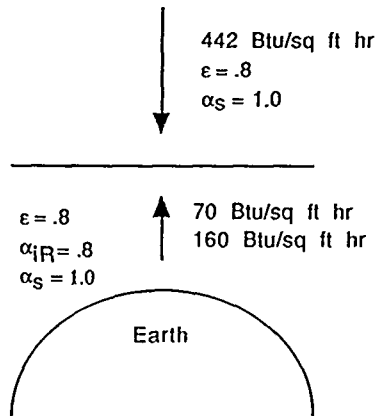


Figure H1. LACE Boom Perpendicular to the Sun

The heat balance equation is

$$\alpha_s s a = \epsilon \sigma T^4 D$$

where s is solar flux intensity, a is surface area and σ is Stefan Boltzman constant.

$$\text{Heat in} = 442 \times 1.0 \times d + (160 \times 1.0 + 70 \times .8) \times \pi d/2$$

$$= 781.3 \text{ d}$$

$$\text{Heat out} = 0.8 \times \pi d \times \sigma \times T^4$$

$$781.3 = 0.9 \times \pi \times \sigma \times T^4 = 4.305 \times 10^{-9} T^4$$

$$T = 652 \text{ R} = 193 \text{ F}$$

B. MINIMUM TEMPERATURE FOR THE DIAGONAL

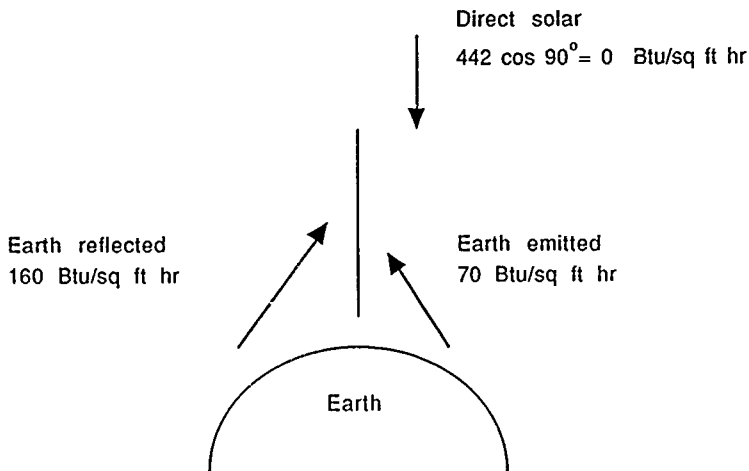


Figure H2. LACE Beam Parallel to the Sun

$$F_{d1-2} = .256$$

$$\text{Reciprocity } F_{d1-2} dA_2 = F_{2-d1} A_2 \Rightarrow \frac{F_{2-d1}}{dA_1} = \frac{.256}{dA_1}$$

$$Q_{2-1} = A_2 F_{2-d1} (E_{b2})$$

$$\text{Divide by } dA_1 \quad \frac{Q_{2-1}}{dA_1} = A_2 \frac{F_{2-d1}}{dA_1} E_{b2}$$

$$\text{Substitute } \frac{Q_{2-1}}{dA_1} = A_2 \frac{.256}{A_2} E_{b2} = 0.28 E_{b2}$$

$$= (0.256) [160 + 70] \text{ Btu/sq ft hr}$$

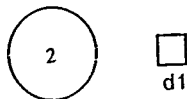


Figure H3. Viewing Factor

$$= 58.9 \text{ Btu/sq ft hr}$$

$$T = \left(\frac{q}{\sigma} \frac{\alpha}{e} \right)^{0.25} = \left(\frac{58.9}{0.1714} \times 10^{-8} 1.25 \right)^{0.25} = 455R = -5F$$

[Ref. 13]

APPENDIX I

```
*****
*                                     *
*  WALTERS, W                       *
*  THESIS RESEARCH                  *
*  6 JUNE 1990                     *
*  NONLINEAR SYSTEMS               *
*                                     *
*****
```

PURPOSE

THIS PROGRAM COMPUTES DISPLACEMENTS, VELOCITIES, AND
ACCELERATION
USING LINEAR ACCELERATION METHOD

VARIABLE DEFINITIONS

```
T=      Time
A=      Acceleration
V=      Velocity
U=      Displacement
M=      Mass
K=      Spring constant
C=      Damping
P=      Force
FS=     Spring force
KSTAR=  Delta K*
PSTAR=  Delta P*
DELT=   Time interval, delta t
DELU=   Change in displacement
DELV=   Change in velocity
DELA=   Change in acceleration
DELP=   Change in force
A0=     Coefficient of amplitude for force function
Omega=  Frequency for force function
A1=     Coefficient for X**3 term for stiffness
        function
B1=     Coefficient for X**2 term for stiffness
        function
C1=     Coefficient for X term for stiffness function
```

```

C      D1=      coefficient for constant term for stiffness
                  function
C      A2=      Coefficient for X**2 term for damping function
C      B2=      Coefficient for X term for damping function
C      C2=      Coefficient for constant term for damping
                  function
C      FRAC=     Fraction of linear stiffness term used for
                  coeff. of cubic term

C
C      ***VARIABLE DECLARATIONS***
C
C      Real*16 T,A,V,U,M,K,C,FS,KSTAR,PSTAR,DELT,DELU,DELV,
*DELA,DELP,A0,Omega,A1,B1,C1,D1,A2,B2,C2,FRAC,MASS,P(5000)
C      DIMENSION P(5000)
C      Integer I,N

C      CHARACTER*7 DUMMY
C      CHARACTER NAME*8, FN*8
C      ***INITIAL DATA***
C
C      T=0.0
C      N=0

C
C      ***MAIN PROGRAM***
C
C      === CREATE A FILE FOR CHAOTIC COMPUTAIONS
C      OPEN (UNIT=1, FILE='ACC.INP', STATUS='OLD')

C
C      WRITE (6,*) 'INPUT THE FILE NAME'
C      READ (5, '(A)') NAME
C      FN = NAME
C      OPEN (UNIT = 12, FILE = FN, STATUS = 'NEW')
C      WRITE(6,*) 'DO YOU WANT INTERACTIVE INPUT FILE,
0=YES,1=NO'
C      READ(5,*) IYES
C      IF (IYES.GT.0) GO TO 500

C
C      PRINT *, 'ENTER INITIAL CONDITIONS'
C      PRINT *, 'INITIAL DISPLACEMENT ='
C      READ *, U
C      PRINT *, 'INITIAL VELOCITY ='
C      READ *, V
C      Print *, 'F(X)=A0*COS(Omega*T)'
C      Print *, 'Enter value for A0'
C      Read *, A0
C      Print *, 'Enter value for Omega'
C      Read *, Omega
C      Print *, 'K(X)=A1*X**3+B1*X**2+C1*X+D1'
C      Print *, 'Enter value for A1'

```

```

Read *, A1
Print *, 'Enter value for B1'
Read *, B1
Print *, 'Enter value for C1'
Read *, C1
Print *, 'Enter value for D1'
Read *, D1
Print *, 'C(X)=A2*V**2+B2*V+C2'
Print *, 'Enter value for A2'
Read *, A2
Print *, 'Enter value for B2'
Read *, B2
Print *, 'Enter value for C2'
Read *, C2
Print *, 'Enter value for mass'
Read *, M
Print *, 'Enter value for delt'
Read *, DELT
Print *, 'Enter value for n, number of time steps'
Read *, N

C
GO TO 550
500 CONTINUE
READ(1,*) A0
READ(1,*) Omega
READ(1,*) A1
READ(1,*) C1
READ(1,*) D1
READ(1,*) A2
READ(1,*) B2
READ(1,*) C2
READ(1,*) M

C
C
WRITE(*,*) A0,Omega,A1,C1,D1,A2,B2,C2,M
PRINT *, 'NONLINEAR STIFF TERM B1 IS FRACTION OF LINEAR
TERM D1'
PRINT *, 'INPUT FRACTION DESIRED'
READ *, FRAC

C
B1= FRAC*D1+D1

C
PRINT *, 'ENTER INITIAL CONDITIONS'
PRINT *, 'INITIAL DISPLACEMENT ='
READ *, U
PRINT *, 'INITIAL VELOCITY ='
READ *, V
Print *, 'Enter value for delt'
Read *, DELT
Print *, 'Enter value for n, number of time steps'
Read *, N
550 CONTINUE

```



```

DUMMY='WALTERS'
Do 20 I=1,K
  Call Force(A0, Omega, T, I, P)
  Call Damp(A2, B2, C2, V, C)
  Call FSPRING(A1, B1, C1, D1, U, I, K, FS)
  CALL DFORCE(T, DELT, I, P)
C
C   Solve for A
C
C    $A = (1/M) * (P(I) - (C * V) - FS)$ 
C
C   Solve for KSTAR
C
C    $KSTAR = K + ((3 * C) / DELT) + ((6 * M) / DELT ** 2)$ 
C
C   Solve for PSTAR
C
C    $PSTAR = DELP + (((6 * M) / DELT) + (3 * C)) * V + ((3 * M) + C * (DELT / 2)) * A$ 
C
C   Solve for DELU
C
C    $DELU = PSTAR / KSTAR$ 
C
C   Solve for DELV
C
C    $DELV = (3 / DELT) * DELU - (3 * V) - A * (DELT / 2)$ 
C
C   Solve for DELA
C
C    $DELA = (6 / DELT ** 2) * DELU - ((6 / DELT) * V) - (3 * A)$ 
C
C   Write output file
C
C *** OUTPUT TO THE CHAOTIC FILE
  WRITE(11, 6000) DUMMY, T, U, V, A
6000 FORMAT(A7, F6.3, E11.4, 4E12.4)
C
C   Update U, V, T for next iteration
C
C   U=U+DELU
C   V=V+DELV
C   T=T+DELT
20 Continue
C
C   Write(*,*)T,U,V
C   CLOSE(UNIT=i)
C   CLOSE(UNIT=11)
C   Stop
C   End
C
C

```

```

C
*****
C
    Subroutine Force(A0,Omega,T,I,P)
C
C    Assigns a value to force based on time
C    Input argument
C    A0-Coefficient,Omega-frequency,T-Time, I-Counter
C    Output argument
C    P-Force
C
    Real*16 A0,Omega,T,P
    Integer I
    DIMENSION P(5000)
C
C
C    Define results
C
    P(I)=A0*COS(Omega*T)
C    Write(*,*)I,P(I)
    Return
    End
C
C
*****
C
    Subroutine Damp(A2,B2,C2,V,C)
C
C    Assigns a value for damping
C    Input argument
C    A2,B2,C2 - Coefficients of damping function
C    U-Displacement
C    Output argument
C    C-Damping
C
    Real*16 A2,B2,C2,V,C
C    Define results
C
    C=A2*V**2+B2*V+C2
    Return
    End
C
C
*****
C
    Subroutine FSPRING(A1,B1,C1,D1,U,I,K,FS)
C
C    Calculates the value for FS
C
C    Input arguments

```

```

C
C   U-Displacements
C   A1,B1,C1,D1- Coefficients for stiffness function
C   I-counter
C
C   Output arguments
C
C   FS-Force of spring
C
C   Real*16 A1,B1,C1,D1,U,FS,K
C   Integer I
C
C   Define results
C
C   K=A1*U**3+B1*U**2+C1*U+D1
C   FS=K*U
C   Return
C   End
C
C
C *****
C
C   Subroutine DFORCE(T,DELP,I,P)
C
C   Defines the value for the change in force
C
C   Input argument
C   T-Time,P-Force
C   Output argument
C   DELP-Change in force
C   Real*16 T,DELP,F,P(5000)
C   INTEGER I
C   DIMENSION P(5000)
C
C
C   IF (I.EQ.1) Then
C       DELP =0
C   ELSE
C       DELP=P(I)-P(I-1)
C   Endif
C   Return
C   End
C
C *****

```

APPENDIX J

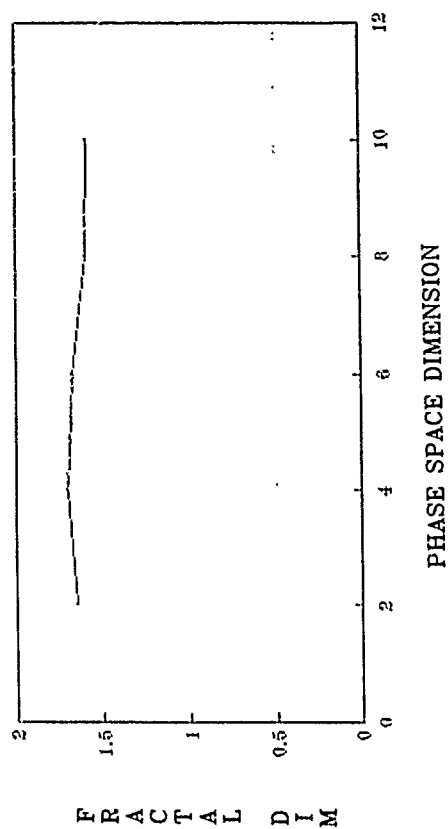


Figure J1. Fractal Dimension. $F=41.68$, $D=1.53$, $C=.177$

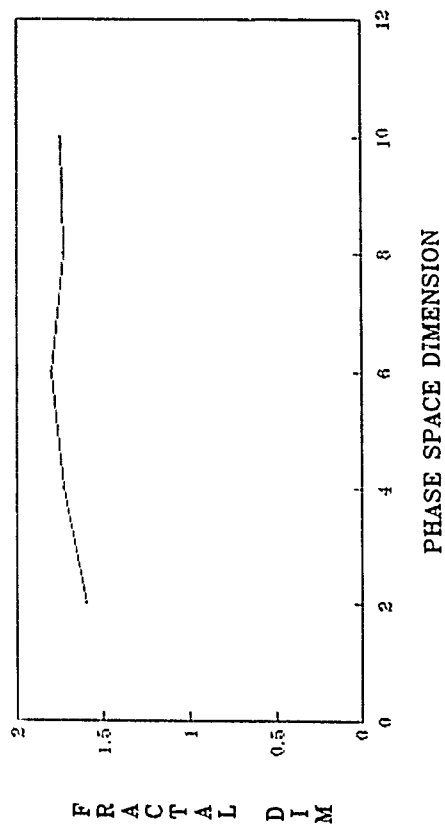


Figure J2. Fractal Dimension. $F=83.35$, $\Omega=1.53$, $C=.177$

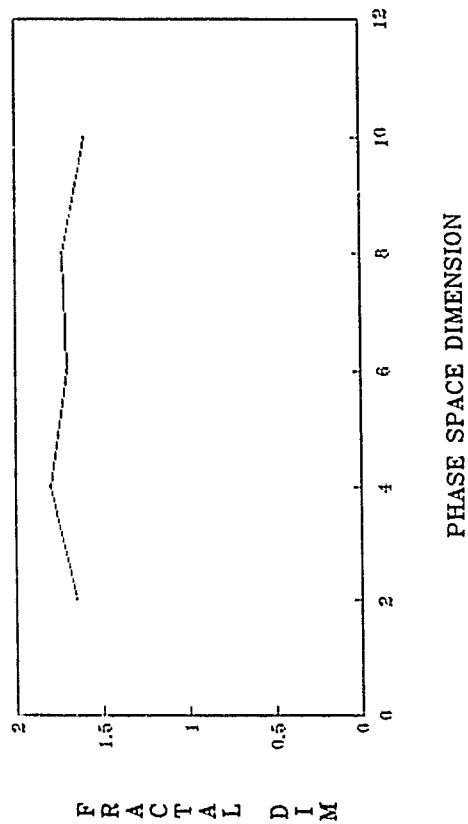


Figure J3. Fractal Dimension. $F=166.7$, $\Omega=1.53$, $C=.177$

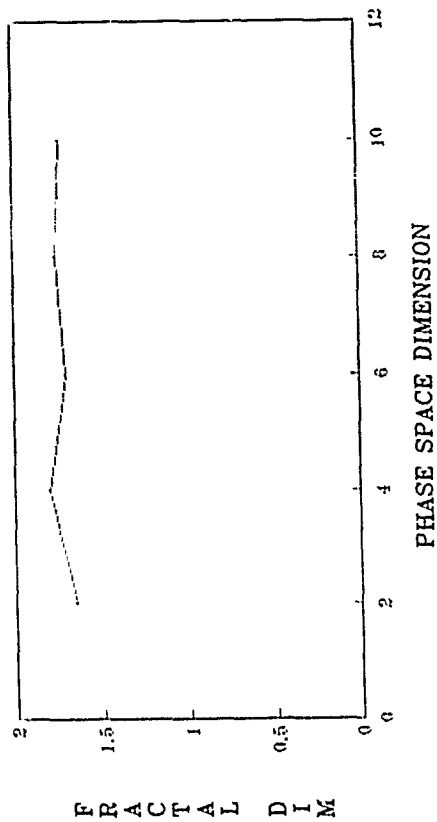


Figure J4. Fractal Dimension. $F=208.4$, $\Omega=1.53$, $C=.177$

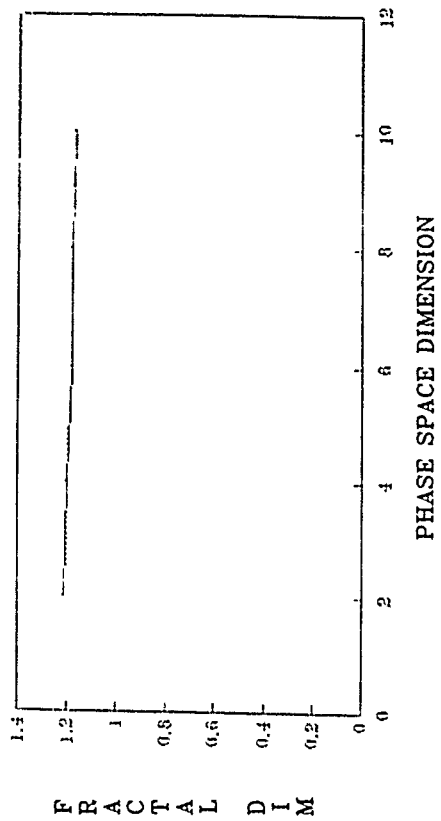


Figure J5. Fractal Dimension. $F=20.8$, $\Omega=13.8$, $C=.177$

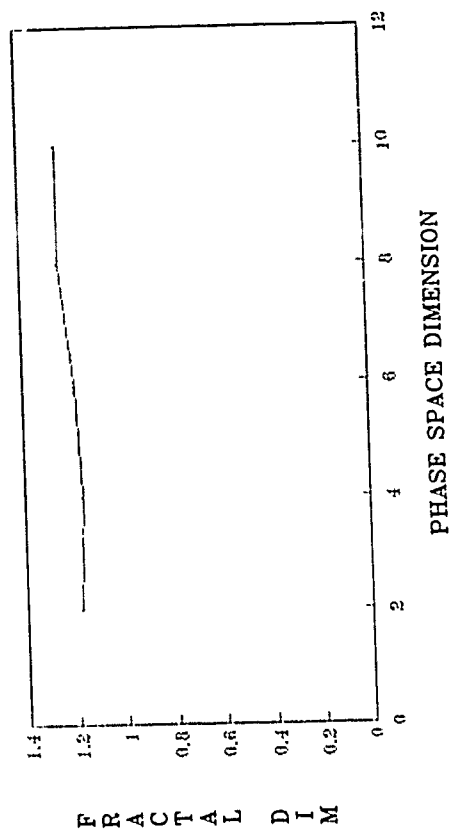


Figure J6. Fractal Dimension. $F=41.68$, $\Omega=13.8$, $C=.177$

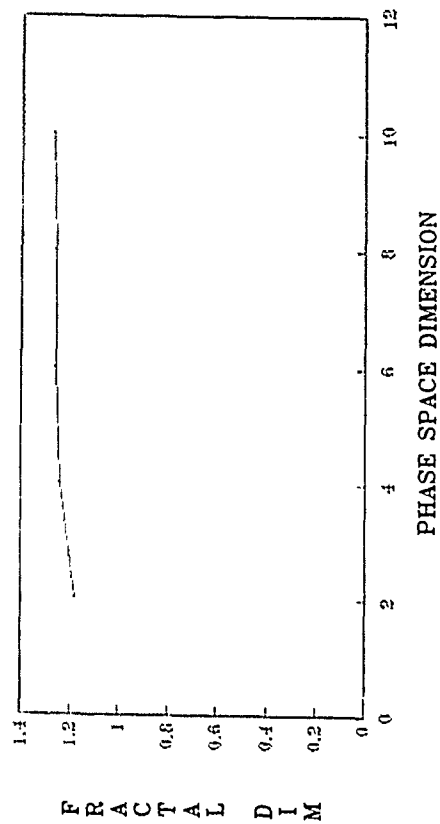


Figure J7. Fractal Dimension. $F=83.35$, $\Omega=13.8$, $C=.177$

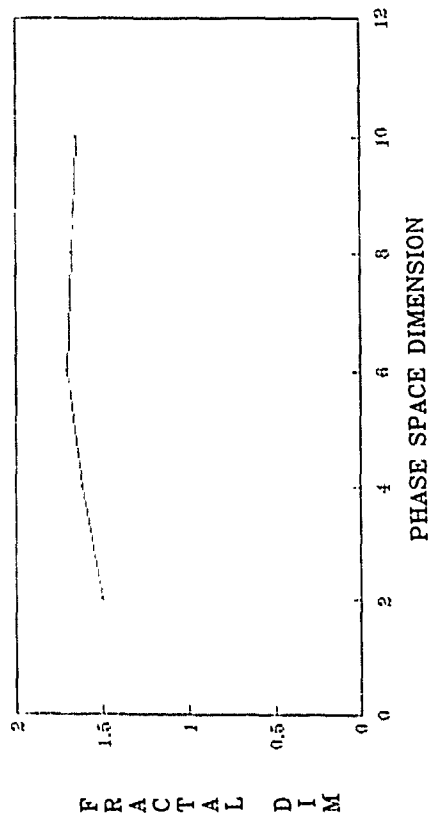


Figure J8. Fractal Dimension. $F=166.7$, $\Omega=13.8$, $C=.177$

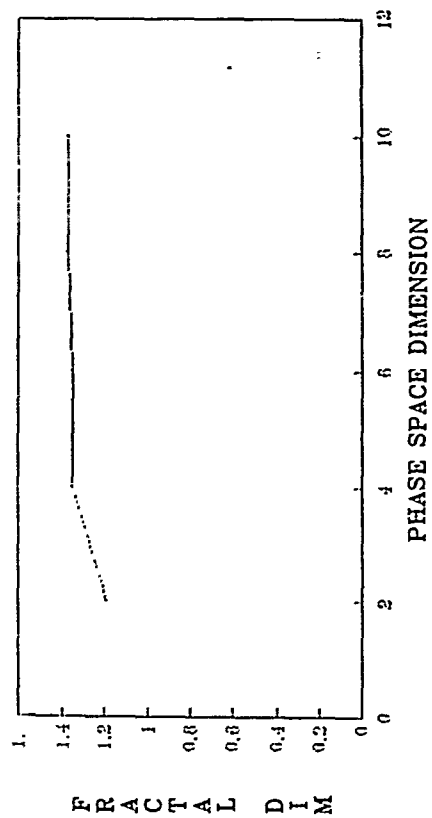


Figure J9. Fractal Dimension. $F=208.4$, $\Omega=13.8$, $C=.177$

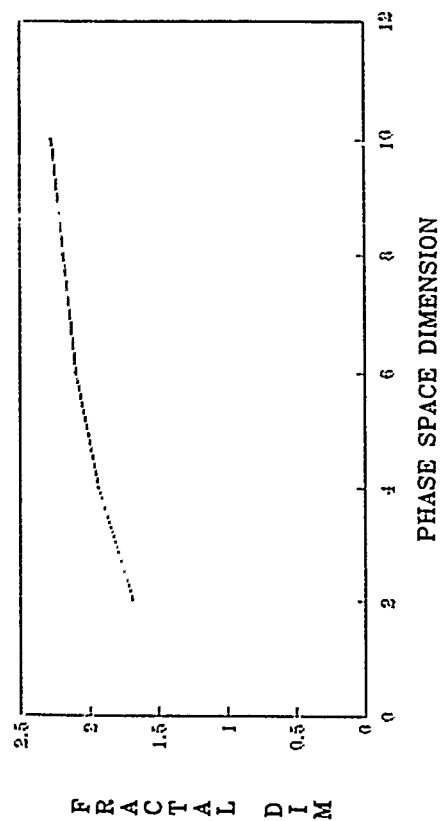


Figure J10. Fractal Dimension. $F=41.68$, $\Omega=1.53$, $C=.0454$

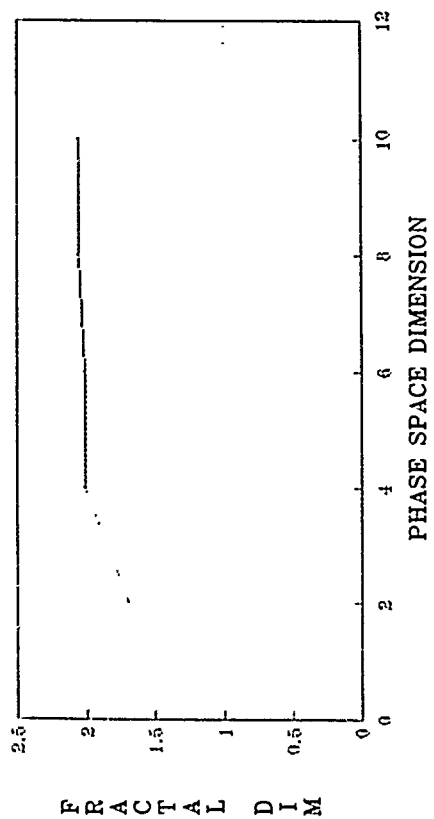


Figure J11. Fractal Dimension. $F=83.35$, $Q=1.53$, $C=.0454$

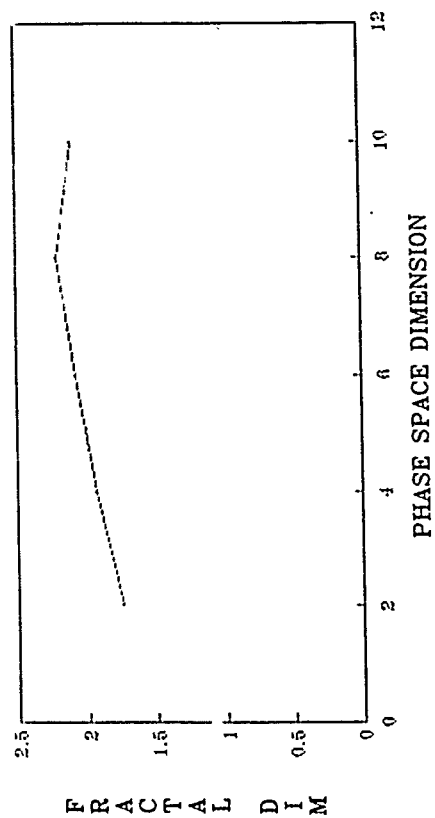


Figure J12. Fractal Dimension. $F=166.8$, $D=1.53$, $C=.0454$

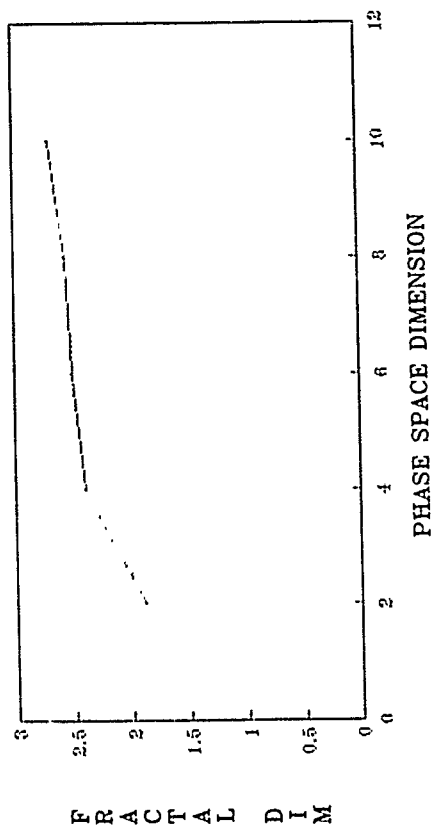


Figure J13. Fractal Dimension. $F=208.4$, $\Omega=1.53$, $C=.0454$

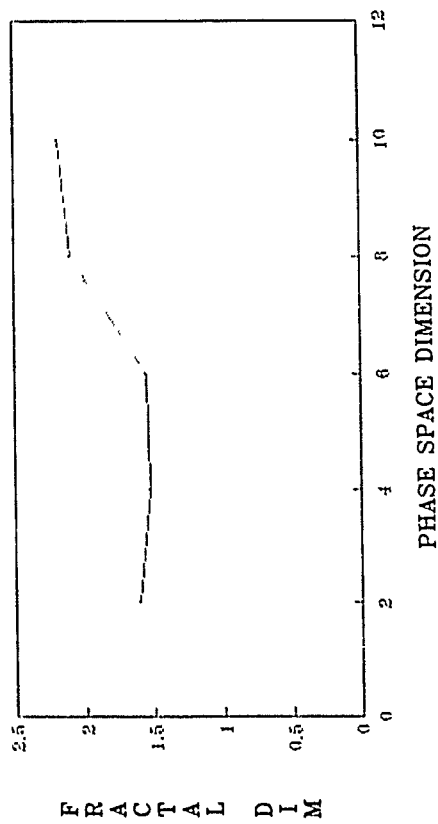


Figure J14. Fractal Dimension. $F=20.8$, $\Omega=13.8$, $C=.0454$

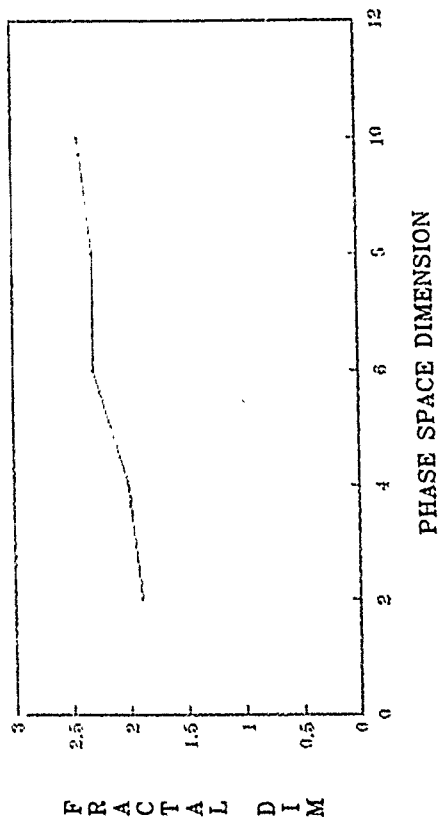


Figure J15. Fractal Dimension. $F=41.68$, $\Omega=13.8$, $C=.0454$

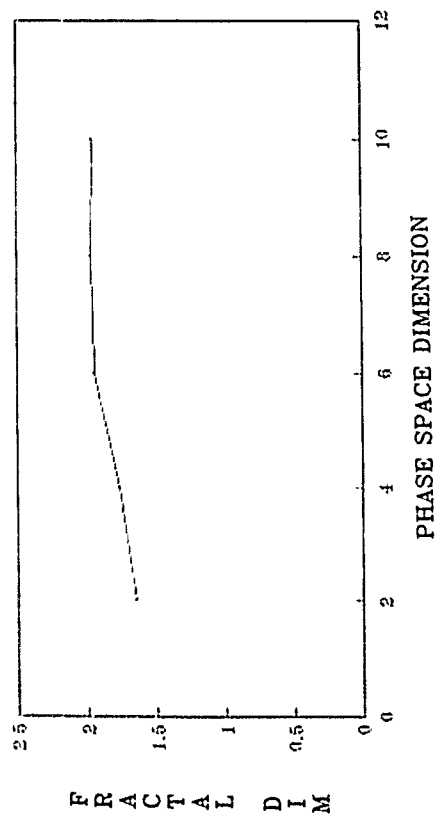


Figure J16. Fractal Dimension. $F=83.35$, $\Omega=13.8$, $C=.0454$

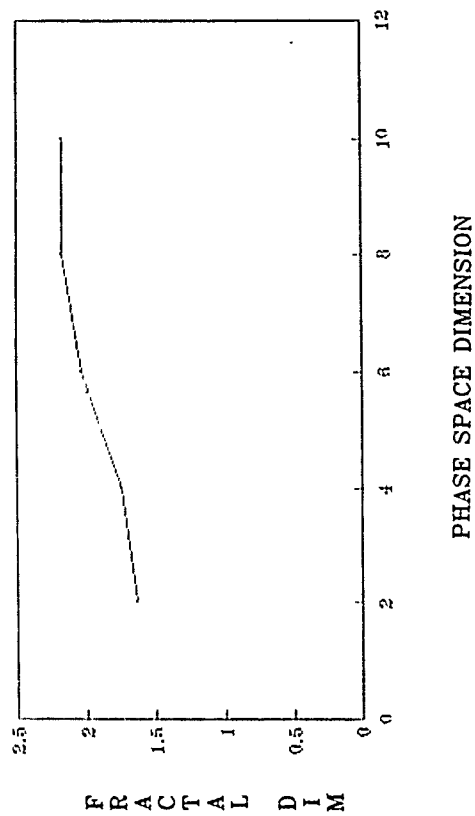


Figure J17. Fractal Dimension. $F=166.7$, $Q=13.8$, $C=.0454$

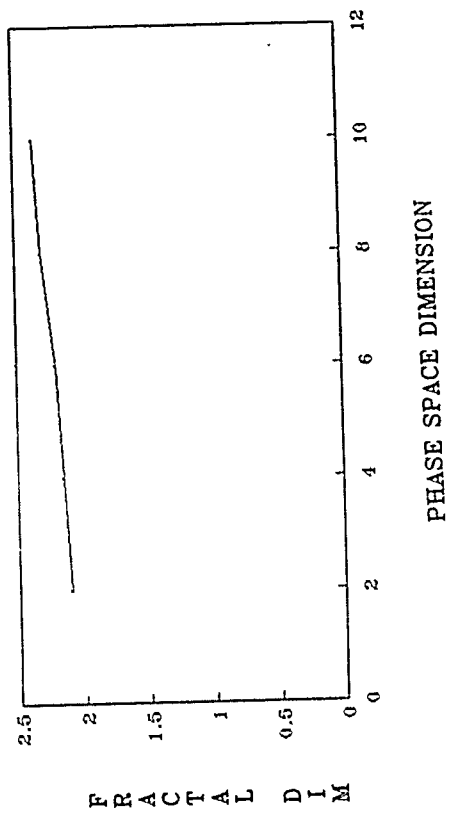


Figure J18. Fractal Dimension. $F=208.4$, $Q=13.8$, $C=.0454$

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